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停車費與擁擠稅之比較－臺北都會區案例

A COMPARISON OF PARKING FEES AND CONGESTION TOLLS−A CASE STUDY FOR THE TAIPEI METROPOLITAN AREA

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摘　要

本文比較管制性的停車費與道路定價；首先，建立一個包含兩種運具選擇方案的模型，停車搜尋行為以整體性的方式處理，明確而言，搜尋車位的時間成本決定於該地區的整體需求與整體供給的比例，通勤旅次必須在市中心或衛星都市的邊緣停車。以臺北都會區的個案分析結果發現，若每一通勤旅次具相同起迄且有停車需求，則最適停車費很接近最適擁擠道路定價的效果。最後，進行模型中參數微量變動的敏感度分析。

關鍵詞： 停車費；擁擠稅；外部性；通勤旅次

ABSTRACT

A regulatory parking fee is compared with road pricing. A commuting trip demand model with two alternative modal choices is developed. The behavior of searching for a parking lot is treated by an aggregate approach. Specifically, the time cost of searching for a parking space depends on the ratio of aggregate

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demand and aggregate supply in an area. Parking either in the CBD or at the boundary of the satellite city is needed for commuting trips. For the case of the Taipei metropolitan area, it is found that the performance of optimal parking fee is close to the first-best optimum road pricing if the parking demand is unavoidable for every commuting trip with the same origin-destination pair. Some sensitivity analyses are conducted for a small change in each parameter in the model.

Key Words: *Parking fee; Congestion tax; Externality; Commuting trip*

I. Introduction

Traffic congestion is a serious problem in many cities. Levying a congestion tax following Pigou [1] is a typical approach to lessen the congestion problem by decreasing the demand for transportation, since investment in road capacity to increase supply may incur latent demand on the roads and cause financial pressure on local government. A Pigouvian tax paid by road users is intended to internalize the congestion externality to reach an efficient traffic volume in a transportation system. The external cost as well as the private user cost can thus be shifted to the road users, decreasing transportation demand. This approach can reach the maximal social surplus, which is measured by the total benefits of road users minus the total costs. However, the congestion tax is sometimes not easily accepted by the public. There are some other ways to lessen the congestion, including gasoline taxation, parking fees, subsidies of public transit and so on. The policy of parking fees is accepted by the public due to provision of the facility (parking space) they use. Generally, it is common to charge a high parking fee to users in a city center.

In the literature on parking issues, some studies focus on the behavior of searching for a parking space and the related economic outcomes. Arnott and Rowse [2] present a model of parking congestion focusing on drivers' search for a vacant parking space in a spatially homogenous metropolis. Arnott and Inci [3] explore cruising for parking from an economic perspective. They present a downtown parking model that integrates traffic congestion and saturated on-street parking. In addition, Arnott [4] determines the equilibrium garage parking fee and spacing between parking garages. Arnott and Rowse [5] present an integrated model of curbside parking, garage parking, and traffic congestion. The results is that raising curbside parking fees appears to be a very attractive policy, since it generates efficiency gains that may be several times as large as the increased revenue raised. However, these debates on downtown parking policy have overlooked downtown parking capacity. Arnott et al. [6] focuses on how much curbside to allocate to parking when the private sector provides garage parking.

Another attractive parking issue is to examine parking policy as well as some congestion pricing regulations. Many studies concentrate on the optimal pricing in bottleneck models. The effect of parking fees on morning peak-hour traffic congestion is explored under various setting for parking market in bottleneck models (Arnott et al., [7]; Qian et al. [8]). Then using the setting of Arnott et al. [7], Zhang et al. [9] combine the morning and evening commuters to derive an overall pattern for the day. It is shown that a combined morning and evening parking fee is more efficient than a parking fee only in the morning or a fee only in the evening (Fosgerau and de Palma [10]). Can parking policy be used to substitute for road pricing? Verhoef et al. [11] analyze this problem by focusing on the differences between the use of a parking fee and physical restrictions on parking space supply. The former is found to be superior based on an information argument, a temporal efficiency argument and an intertemporal efficiency argument. Calthrop, Proost, and van Dender [12] use a numerical simulation model to examine the efficiency gains from various parking policies with and without a simple cordon system. They show that the pricing of parking and road use need to be simultaneously determined. The model results show that the second-best pricing of all parking spaces produces higher welfare gains than the use of a single ring cordon scheme. Calthop and Proost [13] develop a model to study optimal government regulation of the on-street parking market. A driver has two strategies: He/she either parks at a private off-street facility or searches for a cheaper on-street spot. It is shown that the optimal on-street fee equals the marginal cost of off-street supply at the optimal quantity. On the empirical studies, some papers compare the performance of road pricing with parking pricing. Baldassare et al. [14] show that road drivers are more sensitive to parking pricing. Shiftan and Golani [15] find most workers and non-workers would respond to change the travel mode. Bonsall and Young [16] explores the possibility that the removal of parking charges might be a good mechanism to help public acceptance when road charges are employed. The removal of parking charges would reduce revenues but the road charges will decrease travel demand. They suggest that the combined effect might, in certain circumstances, be more beneficial to the local economy and might still yield a net increase in revenue. Chu and Tsai [17] examine an environmental-friendly parking policy to reduce vehicle-mile traveled, and results in lower greenhouse gas emissions. They explore the behavior of chained-trips for setting an environmental-friendly parking fee. A minimum parking fee to reduce vehicle mileage is suggested after the analysis for some parking policies. Albert and Mahalel [18] find travel demand to be much highly elastic with respect to road congestion pricing than parking pricing. However, Azari et al. [19] find that drivers are more sensitive to parking charges than to cordon tolls. [3]

From the above review, it is found that the comparison between road pricing and parking pricing yields various outcomes except that optimal Pigouvian pricing is more efficient than parking pricing. Then, is it possible that the parking pricing is close to the optimal Pigouvian

3. See Inci [20] for a review.

pricing in efficient perspective? This article is intended to answer this question. We develop a model in which the net benefit of parking pricing is compared with a congestion toll from the efficient perspective. The application of this model to the case of the Taipei metropolitan area shows that the parking pricing can yield closely effect with optimal pricing in efficient perspective under some conditions.

In the central business district of a city, it is not easy to find a parking spot on weekdays due to the large demand relative to the parking supply. The parking fee is generally higher in these areas than in other areas. It is common to charge users by price differentiation on parking fees. In the setting of our model, the commuters can make a modal alternative choice. Each commuter needs either parking in the CBD or parking in the boundary of the center city and the surrounding city. The behavior of searching for a parking space is treated by an aggregate approach. Specifically, the time cost of searching for a parking space depends on a ratio of aggregate demand and aggregate supply in an area. That is, the more parking demand there is, the more time will be spent searching for a parking space. The more parking supply, the less searching time for a parking space. Optimal parking fee and optimal congestion pricing are compared. The remainder of this paper is as follows. In Section 2, the model of modal alternative choice is developed. In Section 3, the equilibrium analysis is conducted, and the optimal congestion tax and optimal parking fee are found. The model and the approach of the analysis are then applied to the case of Taipei metropolis in Section 4. Finally, Section 5 provides the conclusions.

II. The model

It is assumed that there is a road providing the transportation supply between a center city and a surrounding city. In the morning rush hours, there are commuting trips from the surrounding city (city 0) to the CBD of the center city (city 1). The inverse demand function for the transportation is denoted by P(Q), where Q is the number of trips. The commuters have two alternatives: [4]

Alternative A: Driving directly from city 0 to the CBD of city 1, searching for a parking space, and walking to the destination after parking.

Alternative B: Driving from city 0 to the boundary of these two cities, searching for a parking space, and walking to take the mass transit to the destination.

4. In reality, there are many alternatives or modes for the commuting. Due to our focus being on the comparison between parking fee and congestion toll, the study employs the commuting alternatives which can be chosen by trading off parking cost and congestion costs.

The trips by alternative A are denoted by Q_A and those by alternative B are Q_B. The costs for the trips by alternative A (by automobile only) and by alternative B (by automobile and mass transit) are:

$$C_A = C_0 + C_1 + C_{p1}, \tag{1}$$

$$C_B = C_0 + C_{p0} + t_f, \tag{2}$$

where C_0 is the driving cost from city 0 to the boundary of these two cities, C_1 is the driving cost from the boundary to the CBD of city 1, t_f is the mass transit fee, C_{p1} and C_{p0} are the costs of parking in the CBD of city 1 and at the boundary of city 0, respectively.

Driving costs are the costs during the automobile driving period. The function form used in the Urban Transportation Planning Package (UTPP) [5] is employed.

$$C_0 = \mu\bar{t_0}\left[1 + \alpha\left(\frac{V_A+V_B}{K_0}\right)^{\beta}\right], \tag{3}$$

$$C_1 = \mu\bar{t_1}\left[1 + \alpha\left(\frac{V_A}{K_1}\right)^{\beta}\right], \tag{4}$$

where μ is value of time, $\bar{t_0}$, $\bar{t_1}$ are the travel time without congestion from city 0 to the boundary, and from the boundary to the CBD of city 1, respectively. K_0, K_1 are road capacity for the road between city 0 and the boundary and that between the boundary and the CBD of city 1; V_A, V_B are traffic volumes, which are calculated by dividing trips Q_A, Q_B, by vehicle occupancy, ρ passengers per vehicle. The parameters α and β are normally set by 0.15 and 4. Note that traffic volume on the road between city 0 and the boundary includes that by the two modal alternatives. In addition, the time costs increase in the ratio of traffic volume and road capacity. That is, this cost will increase as traffic volume increases, and will decrease as road capacity increases.

Parking costs include the searching costs, parking fee, and cost of walking as follows:

$$C_{p1} = C_{s1} + p_1 + C_{w1}, \tag{5}$$

$$C_{p0} = C_{s0} + p_b + C_{w0}. \tag{6}$$

Searching costs are the time cost of searching for a parking space. These costs increase as parking demand increases and decrease as parking supply increases. The function forms are: [6]

5. This form is attributed by Kraus et al. [21] to Solow and Vickery [22]; see Branston [23] for a detailed account of its history and theory.
6. The major part of searching costs for a parking space is the time costs. The estimation for searching cost employs the aggregate approach which is based on the economic law of demand. Specifically, the

$$C_{s1}=\mu\bar{t_s}\left(\frac{V_A}{S_1}\right), \tag{7}$$

$$C_{s0}=\mu\bar{t_s}\left(\frac{V_B}{S_b}\right), \tag{8}$$

where S_1, S_b are number of parking spaces supplied in city 1 and at the boundary of city 0, respectively, $\bar{t_s}$ is the time spent searching for a parking space when parking demand (traffic volume) is equal to parking supply.

Walking costs are the time cost of a commuter walking to his destination after parking. Similarly, these costs will increase as parking demand increases and decrease as parking supply increases, because a larger ratio of parking demand to parking supply will incur a larger distance from one's parking space to the destination. The function forms are:

$$C_{w1}=\mu\left(\frac{d}{v}\right)\left(\frac{V_A}{S_1}\right), \tag{9}$$

$$C_{w0}=\mu\left(\frac{d}{v}\right)\left(\frac{V_B}{S_b}\right), \tag{10}$$

where d is the average distance for walking when parking demand (traffic volume) is equal to parking supply, and v is the walking speed of a typical individual.

The total benefit of the system includes the benefit to the road users and the parking revenue of the suppliers of parking spaces. [7] The former is the area under the inverse demand function, which represents the sum of the benefit for each user. The latter is the sum of parking fees paid by the parking users. The total benefits are estimated by considering two types of trips ($Q=Q_A+Q_B$) as follows:

$$TB=\int_0^Q P(q)dq+p_bV_B+p_1V_A. \tag{11}$$

Total costs are the sum of user costs by alternative 1 and those by alternative 2, and the production cost of the parking supplier.

$$TC=Q_AC_A+Q_BC_B+m_bS_b+m_1S_1, \tag{12}$$

where m_b, m_1 are the constant marginal costs of a parking space at the boundary of city 0 and in city 1, respectively. Substituting (1), (2), (5), (6) into (12) yields

cost is increasing in the total number of demand and decreasing in the total number of supply (See Tsai and Chu [24]).

7. Whether the suppliers of parking spaces are private firms or public authorities does not influence the results.

$$TC = Q_A(C_0 + C_1 + C_{s1} + p_1/\rho + C_{w1}) + Q_B(C_0 + C_{s0} + p_b/\rho + C_{w0} + t_f) + m_b S_b + m_1 S_1. \quad (13)$$

Total net benefit is then obtained by subtracting total costs from total benefits:

$$TNB = \int_0^Q P(q)dq - Q_A(C_0 + C_1 + C_{s1} + C_{w1}) - Q_B\left(C_0 + C_{s0} + C_{w0} + t_f\right) - m_b S_b - m_1 S_1. \quad (14)$$

Note that the parking revenue collected from parking fees is a transfer payment from the parking consumers to the parking suppliers which disappears in TNB. However, this parking fee is a cost item to the commuters, and thus will decrease the number of trips. The decision of how high to set parking fees can be used to influence trip numbers and thus reach the goal of welfare maximization.

III. Equilibrium analysis, optimal congestion tax, and optimal parking fee

In this section, the welfare with the optimal parking fee is analyzed for comparison with the optimal congestion tax of Pigouvian taxation. In addition, the equilibrium situation without any taxation is analyzed to serve as a benchmark for comparing the level of welfare improvement by the two approaches above. Three regimes are thus analyzed as follows.

Regime I: Equilibrium analysis with no congestion toll

The commuters will make their trips following the principle of marginal benefit equal to the user cost (average cost) by each alternative to the CBD of city 1 in the situation of no congestion tax. The condition is thus:

$$P(Q) = C_0 + C_1 + C_{s1} + \frac{p_1}{\rho} + C_{w1}, \quad (15)$$

$$P(Q) = C_0 + C_{s0} + \frac{p_b}{\rho} + C_{w0} + t_f, \quad (16)$$

where $Q = Q_A + Q_B$. In this regime, the parking fee at the CBD, p_1, and at the city boundary, p_b, are given exogenously to cover the production costs of parking. This treatment is also used in regime II. Eq. (15) and Eq. (16) are derived from the equilibrium concept, which is similar to Wardrop's first principle (Wardrop [25]). The principle demonstrates that the travel costs on two roads available are the same in equilibrium; otherwise, road users will shift from one road to the other. In this case, the commuters will shift to the other modal alternative if the two alternatives incur different user costs.

Regime II: Optimal congestion taxation

Levying a congestion tax on the road users is intended to lessen the traffic congestion and to reach efficient road usage. The goal of this approach is to maximize the welfare of the system, which is normally measured by the total net benefit. This problem is thus expressed as: [8]

$$max_{Q_A,Q_B}\ \ TNB = \int_0^Q P(q)dq - Q_A(C_0 + C_1 + C_{s1} + C_{w1})$$

$$-Q_B\left(C_0 + C_{s0} + C_{w0} + t_f\right) - m_b S_b - m_1 S_1, \tag{17}$$

$$s.t. Q = Q_A + Q_B. \tag{18}$$

The optimal trips for each modal alternative need to satisfy the following first-order conditions for maximizing the total net benefit of the system (See Appendix A for details).

$$P = (C_0 + C_1 + C_{s1} + C_{w1}) + \frac{Q_A+Q_B}{\rho}\frac{\partial C_0}{\partial V_A} + \frac{Q_A}{\rho}\frac{\partial C_1}{\partial V_A} + \frac{Q_A}{\rho}\left(\frac{\partial C_{s1}}{\partial V_A} + \frac{\partial C_{w1}}{\partial V_A}\right), \tag{19}$$

$$P = \left(C_0 + C_{s0} + C_{w0} + t_f\right) + \frac{Q_A+Q_B}{\rho}\frac{\partial C_0}{\partial V_B} + \frac{Q_B}{\rho}\left(\frac{\partial C_{s0}}{\partial V_B} + \frac{\partial C_{w0}}{\partial V_B}\right). \tag{20}$$

Eq. (19) represents the condition that the marginal benefit is equal to the marginal cost for the user by modal alternative A. These marginal costs include the user's average cost (without parking fee) and the external travel costs and external parking costs from one more trip. The external travel costs are imposed upon the road users by modal alternatives A and B. The external parking costs comprise searching costs and walking costs to the road users by modal alternative A due to the extra searching time and extra distance for walking from one more trip in the system. Eq. (20) represents a similar condition for the user by modal alternative B. Due to the marginal benefits in both equations being the same, it means that the marginal costs by the two modal alternatives are equal in the situation of optimal congestion taxation.

The level of congestion toll for each type of road user is the marginal benefit minus the average costs (the private user cost with no toll). The congestion toll for each type of commuter is:

$$\tau_A = \frac{Q_A+Q_B}{\rho}\frac{\partial C_0}{\partial V_A} + \frac{Q_A}{\rho}\frac{\partial C_1}{\partial V_A} + \frac{Q_A}{\rho}\left(\frac{\partial C_{s1}}{\partial V_A} + \frac{\partial C_{w1}}{\partial V_A}\right) - \frac{p_1}{\rho}, \tag{21}$$

$$\tau_B = \frac{Q_A+Q_B}{\rho}\frac{\partial C_0}{\partial V_B} + \frac{Q_B}{\rho}\left(\frac{\partial C_{s0}}{\partial V_B} + \frac{\partial C_{w0}}{\partial V_B}\right) - \frac{p_b}{\rho}. \tag{22}$$

8. In this problem, price (or tolling level) and quantity are dependent with each other. The determination for each of them will yield the other variable. For calculating reasons, quantity is used for decision variable in this problem. The treatment for this type of problem is used for many studies in road pricing issue such as Liu and McDonald [26], Chu and Tsai [27], and Tsai, Chu, and Hu [28].

This optimal congestion toll for type A commuters in (21) equals three externalities minus the parking payment from road users to parking suppliers. The three externalities result from the increase in commuters by mode alternative A, and include three parts. The first part is the additional travel delay cost on the road users (commuters by both model alternatives) between city 0 and the boundary of these two cities. The second part is the additional delay cost imposed on its own type of commuters between the city boundary and the CBD. The third part is the additional costs imposed on its own type of commuters for searching for parking and walking to the destination. The parking fee per person is subtracted from the above external costs because this fee is a transfer payment to the parking suppliers. The reason is that this parking fee is one part of the commuters' costs, but it is not included in the marginal cost of the system. The congestion toll is to induce the road users to pay the marginal cost of the system for their trips and thus the difference between the marginal cost and user's private cost (average cost) is levied.

The congestion toll for type B commuters in (22) is similar to that of type A commuters. The externality does not include the travel delay from the city boundary to the CBD because these commuters use mass transit instead of automobiles for this part of each trip.

Regime III: Optimal parking fee

Instead of levying a congestion tax on the commuters, a higher parking fee will increase a commuter's trip cost and decrease the trip demand and the traffic volume on roads. The problem can be expressed as [9]

$$max_{p_0,p_1}\, TNB = \int_0^Q P(q)dq - Q_A(C_0 + C_1 + C_{s1} + C_{w1})$$

$$-Q_B\left(C_0 + C_{s0} + C_{w0} + t_f\right) - m_b S_b - m_1 S_1, \tag{23}$$

$$s.t.\;\; P(Q) = C_0 + C_1 + C_{s1} + \frac{p_1}{\rho} + C_{w1},$$

$$P(Q) = C_0 + C_{s0} + \frac{p_{\mathrm{b}}}{\rho} + C_{w0} + t_{f,}$$

$$Q = Q_A + Q_B.$$

The objective is to maximize the total net benefit as that in optimal congestion taxation scheme. However, the decision variables are parking fees at the boundary of city 0 and in city 1. In addition, the commuters will follow their trip behavior with no toll. Specifically, the marginal benefit will equal the commuter's private cost (average cost) by each mode alternative,

9. The parking fees are absent from TNB because this item is transfer payment between the commuters and the parking suppliers. This transfer payment will vanish when welfare (TNB) is evaluated by the sum of consumer surplus and producer surplus.

which is expressed in the constraint. Substituting the two constraints into the objective function yields: [10]

$$max_{p_b,p_1} TNB = \int_0^Q P(q)dq - P(Q)(Q_A + Q_B) + \frac{Q_B p_b}{\rho} + \frac{Q_A p_1}{\rho} - m_b S_b - m_1 S_1. \tag{24}$$

Note that trip number, Q_A, Q_B, and commuters' marginal benefit, P(Q), are all functions of the parking fees in city 0 and in city 1. Differentiating (24) with respect to parking fees, p_b and p_1, yields the following first-order conditions:

$$\frac{dP}{dQ}\frac{\partial Q}{\partial p_b}(Q_A + Q_B) = \frac{p_1}{\rho}\frac{\partial Q_A}{\partial p_b} + \frac{p_b}{\rho}\frac{\partial Q_B}{\partial p_b} + \frac{Q_B}{\rho}, \tag{25}$$

$$\frac{dP}{dQ}\frac{\partial Q}{\partial p_1}(Q_A + Q_B) = \frac{p_1}{\rho}\frac{\partial Q_A}{\partial p_1} + \frac{p_b}{\rho}\frac{\partial Q_B}{\partial p_1} + \frac{Q_A}{\rho}. \tag{26}$$

Eq. (25) represents the commuters' additional benefit due to the fact that the smaller number of commuters resulting form the higher parking cost is equal to the additional parking revenue of the parking suppliers at the boundary of city 0 and those in city 1 due to the increase of parking fee at the boundary of city 0. Eq. (26) is similar to Eq. (25) and represents the condition of the increase of parking fee in city 1. [11]

The above results of the three regimes are based on the assumptions of a closed system with one road section. All the commuters have the same O-D pair and only one road to use. In reality, the commuters may have multiple O-D pairs and multiple roads to use. However, the purpose of this paper is to explore the effects of parking fees and congestion tolls. The multiple O-D pairs can be simplified to an O-D pair without changing the effect on total net benefit as well as the congestion externality.[12] In addition, multiple parallel roads with the same direction from city 0 to city 1 can be simplified to one road with the summation of all the trips and capacities of the multiple roads. This simplification is employed in the case of Taipei Metropolitan Area in the next section.

10. In the objective function $C_0 + C_1 + C_{s1} + C_{w1}$ can be substituted by $P(Q) - p_1/\rho$ from the first constraint. Similarly, $C_0 + C_{s0} + C_{w0} + t_f$ can be substituted by $P(Q) - p_b/\rho$ from the second constraint.
11. However, it is difficult to solve this problem directly from the first order conditions though these conditions provide economic interpretations for the system. The solution is obtained by the numerical simulations.
12. The concept of average is used for this simplification. In multiple O-D pairs, some trips with longer distance incur more congestion externalities while others do less congestion externalities. A representative O-D with the total trips will get the same effects of multiple O-D pairs.

IV. The case of Taipei Metropolitan Area

This section applies the model outlined in the previous section to the Tucheng city－Banciao city－Taipei CBD corridor in the Taipei metropolitan area in Taiwan. The commuters from the southwest side of Taipei, including Tucheng city and Banciao city in the metropolitan area, utilize this corridor when traveling to the Taipei CBD. To avoid a multiple origin-destination pair for the trip demand pattern, Tucheng city and Banciao city are formulated as a combined surrounding city (or a zone), and a centroid of this zone is used to estimate the demand function from this centroid to the Taipei CBD. The demand function is assumed to be linear for the commuters from the satellite city to the Taipei CBD as follows: [13]

$$Q = a - bP. \tag{27}$$

The parameters in the function are estimated by the automobile trip data from Tucheng city to the Taipei CBD (4,986 trips/h) and that from Banciao city to the Taipei CBD (12,757 trips/h) in the morning rush hour. [14] The costs for these two trips are estimated by employing 30 and 50 minutes for travel time respectively, 11.2 minutes [15] for searching for parking spaces and 6 minutes for walking. The time value, μ, is NT\$ 216.6 per hour for each commuter. [16] The typical parking fee is NT\$ 200 per vehicle per day in the Taipei CBD. The parking fee per person for this trip is thus NT\$ 200/2/1.54=64.94. [17] The trip cost from Banciao city to the Taipei CBD and that from Tucheng city to the Taipei CBD are thus NT\$ 235.39 and NT\$ 307.59, [18] respectively. The values for the parameters a and b are thus 38092.3937 and 107.6316. To aggregate the two demands from both Tucheng city and Banciao city to the Taipei

13. Linear trip demand is a simple function form for the users' behavior. However, it obeys the major feature of principle of demand. Many related studies employs this function form for trip demand functions, for instances, McDonald [29], Liu and McDonald [26], Chu and Yeh [30], Tsai, Chu, and Hu [28].
14. These trip data are from Institute of Transportation, Ministry of Transportation and Communication, ROC [31]. The number of trip in this study is calculated on the base of one rush hour.
15. The average searching time is from Ministry of Transportation and Communication, ROC [32].
16. The value of time is from Lin and Su [33].
17. This is a typical parking fee per vehicle per day in the Taipei CBD from a personal survey. Assuming that there are two major trips per day for the commuters (one is from home to one's working place and the other is back to home). One half of the parking fee is thus shared by the morning trip from home to the CBD. The parking fee is a joint cost of the two trips going to CBD and back to home. The distribution of a joint cost depends on various theories, which is not emphasized in this study. For a comparison with the other schemes for one-way trip, we distributed half the joint cost to the one-way trip from home to CBD. Otherwise, the comparison will be made on a different base for the cost. This also implies half the parking fee is considered in the trips back to home.
18. These costs include travel time cost, searching and walking cost, and parking cost. The value of the former trip cost is calculated by NT\$216.6/h×47.2min/60min/h+NT\$65=NT\$235.39 and the similar calculation is for the latter trip cost.

CBD, the demand function is thus: Q= 76184.7947-215.2632P. The inverse demand function, which also represents the marginal benefit for the commuters, is: P = 353.9147 - 0.004655Q.

The parameters for the driving costs, $\overline{t_0} = 15\ min$, $\overline{t_1} = 4\ min$ are the travel time without congestion from the centroid of the combined surrounding city to the boundary of Taipei city. The road capacity K_0 and K_1 are 6 lanes and thus 9,000 pcu/h. [19] The value of time, μ, is NT \$ 216.6 /h. The parameter, $\overline{t_s} = 11.2\ min$ is the time for searching for a parking space when parking demand (traffic volume) is equal to parking supply. The number of parking spaces in this corridor of the two cities is $S_1 = 4977$, $S_0 = 1514$. [20] The average distance of walking, d, and walking speed, v, are assumed to be 300 m and 50m/min. [21] The vehicle occupancy, ρ, is 1.54 trips per vehicle. [22] The unit costs for providing the parking space, m_0 and m_1, are assumed to be NT\$ 150 and NT\$ 200 for the parking spaces in the surrounding city and that in Taipei city. The mass transit fee, t_f, is NT\$ 25 for this trip. [23]

The three regimes for equilibrium with no congestion tax, optimal congestion tax, and optimal parking fee are shown in Table 1. [24] The trips and traffic volume in equilibrium (in Regime I) are higher than those in the other two regimes. The optimal congestion taxation in regime II will decrease the traffic demand and generate the highest welfare (total net benefit) by

19. The road capacity per lane (k) is assumed to be 1,500 pcu/h due to some delay from the traffic signals on these roads in comparison with the typical road capacity of 2,000 pcu/h. The number of lanes on these roads are aggregated based on the connecting roads between the origin and destination. There are six lanes including Hua-Jiang Bridge, Kuang-Fu Bridge, Hua-Cui Bridge, and Wan-Ban Bridge after excluding two lanes for other vehicles.
20. The number of parking spaces in the search area in the CBD and non-CBD of the Taipei metropolitan area are provided as follows. Taipei municipal parking lots including roadside parking, off-street parking and contractor for Zhongzheng District, Zhongshan District, Daan District, and Xinyi District in 2016 are 37213 (Taipei City Statistical Yearbook 2016 [34]). The trips from Tucheng city－Banciao city transportation corridor to the Taipei center city are 13.375% of all the trips from all transportation corridors into the Taipei CBD in the morning rush hour (Department of Transportation, Taipei City Government [35]). The parking lots available for Tucheng city－Banciao city transportation corridor are thus S_1 =4977. Due to the data of parking lots for Banciao city is unavailable. It is assumed that the provision of parking lots of local governments depends on the number of population. The number of total parking lots in New Taipei City in 2016 is 107153 (New Taipei City Statistical Yearbook 2016 [36]) and that in Banciao city is thus 14873 from the modification by ratio of population (13.88%). To estimate the number of parking lots near city boundary in the area from which the commuters can take MRT, we use the circular area with a radius of 500 meters of each MRT station for three stations (Banqiao station, Xinpu station and Jiangzicui station) on Bannan Line. Assume the parking lots be uniformly distributed in Banciao city. The area of Banciao city is 23.14 km^2, and the ratio of area is used to calculate the number of parking lots. Thus, $S_b = 14873 \times \frac{3\pi\times0.5^2}{23.14} = 1514$.
21. These values are from a personal survey.
22. The number of vehicle occupancy is from Lin and Su [33].
23. The mass transit fee is from the fare of Taipei Mass Rapid Transit Corporation.
24. The first-order conditions of the model in regime I and regime II are useful for the solutions. For regime III, the approach for the solution is to select the parking fees which can yield the maximal TNB after comparing TNB levels of various parking fees. Instead of developing an algorithm for the solutions, a mathematical calculating software, Maple, is used in this simulations.

levying a congestion tax of NT$ 59.02 and NT$ 68.78 per trip for the trips to the boundary of Taipei city and to the CBD, respectively. Comparing these two taxation regimes, Regime III, which charges an optimal parking fee, will incur smaller traffic volume to the Taipei CBD and smaller total traffic volume than Regime II, while Regime III charges parking fees of NT$ 116.88 and NT$ 123.38 per trip for trips to the boundary of Taipei city and to the CBD, respectively, in comparison with the original parking costs in Regime II of NT$ 48.70 and NT$

Table 1. Equilibrium and optimal trips, benefits, and costs

	Regime I	Regime II	Regime III
P	269.83	289.11	288.90
Q_A	13,657	10,792	10,824
Q_B	4,444	3,159	3,170
V_A	8,868	7,008	7,029
V_B	2,886	2,051	2,059
C_0	77.78	62.49	62.59
C_1	16.48	15.24	15.25
C_{s0}	77.07	54.79	54.98
C_{s1}	72.04	56.93	57.10
C_{w0}	41.28	29.35	29.45
C_{w1}	38.59	30.50	30.59
p_b	48.70	48.70	116.88
p_1	64.94	64.94	123.38
C_{p0}	167.05	132.84	201.31
C_{p1}	175.57	152.36	211.07
C_A	269.83	230.08	288.90
C_B	269.83	220.32	288.90
τ_A	–	59.02	–
τ_B	–	68.78	–
TB	6,748,306	5,339,950	6,203,969
TC	5,495,324	3,790,264	4,654,312
TNB	1,252,982	1,549,686	1,549,657

64.94 per trip for trips to the boundary of Taipei city and to the CBD, respectively. [25] The welfare in Regime III reaches 99.99% of the level in Regime II, while Regime III yields a higher total benefit and higher total cost in comparison with Regime II.

However, this result holds under some conditions from the setting of this model. Firstly, the trips are from the same origin to the same destination. Secondly, all of the trips need parking either at the CBD or the boundary of the central city. The intuition of this result is that trip demand will decrease due to the congestion tax or parking fee if parking behavior is combined with trip demand. In addition, the parking demand (V_A, V_B) is larger than parking supply (S_1, S_b) in both parking markets. This means the parking searching costs in these situations are higher from (7) and (8). It can be interpreted as the users need more waiting time for vacant parking lots due to more potential users competing for parking lots. Another explanation is that some users will utilize the parking spaces out of the system (e.g. the parking spaces in buildings) by contract in advance. The equilibrium parking fee in these parking space will equal the sum of parking fee and searching cost of the parking lots in the system.

Table 2 shows the welfare level associated with various parking fees per day per vehicle for parking at the city boundary and at the CBD. It shows that the maximal welfare level is under the condition of $p_0 =$ NT\$ 360, $p_1 =$ NT\$ 380, which is the case in regime III. Because the parking fee is for one unit of car parking (one parking space for one day), the parking fee for each individual trip is NT\$ 116.88 and NT\$ 123.38, respectively. This means that the additional charge for parking fee for each individual trip is NT\$ 68.18 and NT\$ 58.44.[26] Comparing the additional parking charges in regime III with the congestion tolls in regime II (NT\$ 59.02 and NT\$ 68.78 per trip), they are very similar. However, the additional parking charge for the trips to the boundary of Taipei city is higher than the optimal congestion toll while that to the CBD is lower. This implies that the cross subsidy exists when the optimal parking is employed. The reason is that congestion toll for the trips to the CBD are higher than those to the boundary of Taipei city due to the longer travel distance generating larger congestion externalities. Parking charges evaluate only the amount of parking fee at the destination without considering the externalities due to the travel distance.

25. The parking cost per parking space is transformed to the cost per trip by dividing the vehicle occupancy and the number of trip directions. For example, the parking cost per trip to the boundary of Taipei is NT\$ 150/1.54/2= NT\$ 48.70. The parking fee per parking space in Regime III is NT\$ 360 and NT\$ 380 (see Table 2) for the trips to the boundary of Taipei city and to the CBD, respectively.
26. The additional parking charges are calculated by subtracting the constant parking fees in regime II, NT\$ 48.70 and NT\$ 64.94 per trip, from the optimal parking fees in regime III, NT\$ 116.88 and NT\$ 123.38 per trip.

Table 2 Welfare with various parking fees in CBD and non-CBD

(NT$)

P_b \ P_1	350	360	370	380	390	400
350	1542063	1546079	1548471	1549230	1548348	1545819
360	1541586	1545906	1548599	1549657	1549075	1546842
370	1540409	1545031	1548025	1549383	1549098	1547163
380	1538530	1543454	1546748	1548405	1548418	1546779
390	1535951	1541176	1544770	1546725	1547034	1545691
400	1532670	1538195	1542088	1544341	1544947	1543899

Note that parking cost is a joint cost for the trip from home to the CBD and that from the CBD back to home. Table 1 shows the result of the trip of one direction (from home to the working place) by allocating the parking cost equally to the round trips. To take into account the round trips and the parking costs without allocation, twice the original demand are considered. The result is shown in Table 3. It includes the total benefits, total costs, and total congestion toll for the round trips. Specifically, the congestion toll for the trips of each direction is NT$ 59.02 and NT$ 68.78 per trip to the boundary of Taipei city and to the CBD, respectively. This charging amount is equal to that for the trips of the direction from home to the CBD in Table 1. However, the congestion toll will be NTT$ 118.04 and NT$ 137.56 per trip if the trips from the CBD to home is not charged.

Sensitivity analyses are made by increasing each parameter by 20% in each regime in the model for the round trips. Table 4- Table 6 show the outcomes of these sensitivity analyses for equilibrium with no regulation, optimal congestion taxation, and optimal parking fee. In case 1, as the maximum potential demand (parameter a) increases, the number of equilibrium trips in regime A and the number of optimal trips in regime B and in regime C increase. Trips by both modal alternative A and modal alternative B increase in each regime. The marginal benefit and average cost in each regime increase. This also induces a higher optimal congestion tax and higher optimal parking fee for road users. The total net benefit increases due to the higher demand.

Table 3 Equilibrium and optimal trips, benefits, and costs for round trips

	Regime I	Regime II	Regime III
P	539.66	578.22	577.80
Q_A	27,314	21,584	21,648
Q_B	8,888	6,318	6,340
V_A	17,736	14,016	14,058
V_B	5,772	4,102	4,118
C_0	155.56	124.98	125.18
C_1	32.96	30.48	30.50
C_{s0}	154.14	109.58	109.96
C_{s1}	144.08	113.86	114.20
C_{w0}	82.56	58.70	58.90
C_{w1}	77.18	61.00	61.18
p_b	97.40	97.40	233.76
p_1	129.88	129.88	246.76
C_{p0}	334.10	265.68	402.62
C_{p1}	351.14	304.72	422.14
C_A	539.66	460.16	577.80
C_B	539.66	440.64	577.80
τ_A	–	118.04	–
τ_B	–	137.56	–
TB	13,496,612	10,679,900	12,407,938
TC	10,990,648	7,580,528	9,308,624
TNB	2,505,964	3,099,372	3,099,314

Table 4 Sensitivity analysis for Regime I

	Case 1	Case 2	Case 3	Case 4	Case 5
P	645.58	473.96	561.06	530.86	510.34
Q_A	33,060	22,576	23,748	28,814	32,258
Q_B	10,812	7,366	7,848	9,282	10,254
V_A	21,468	14,660	15,420	18,710	17,456
V_B	7,020	4,782	5,096	6,028	5,548
C_0	210.24	130.40	162.86	136.24	151.64
C_1	37.64	30.78	37.46	31.32	32.72
C_{s0}	187.50	127.72	163.30	160.98	148.16
C_{s1}	174.40	119.08	150.32	152.00	141.80
C_{w0}	100.44	68.42	87.48	86.24	79.38
C_{w1}	93.42	63.8	80.54	81.42	75.96
p_b	97.40	97.40	97.40	97.40	81.16
p_1	129.88	129.88	129.88	129.88	108.22
C_{p0}	385.34	293.54	348.20	344.60	308.72
C_{p1}	397.70	312.76	360.74	363.30	326.00
C_A	645.58	473.96	561.06	530.86	510.34
C_B	645.58	473.96	561.06	530.86	510.34
TB	19,070,694	9,787,338	11,947,030	14,120,254	15,108,188
TC	15,384,366	8,317,650	10,085,894	11,334,204	12,070,178
TNB	3,686,328	1,469,688	1,861,136	2,786,050	3,038,010

Note: Case 1: a increases 20%; Case 2: b increases 20%; Case 3: μ increases 20%; Case 4: k increases 20 %; and Case 5: ρ increases 20%.

Table 4 Sensitivity analysis for Regime I (Continued)

	Case 6	Case 7	Case 8	Case 9	Case 10
P	540.36	536.48	531.32	548.16	541.06
Q_A	27,482	26,526	29,798	25,930	26,900
Q_B	8,568	10,358	8,196	8,438	9,000
V_A	17,846	17,224	19,348	16,838	17,468
V_B	5,564	6,726	5,322	5,480	5,844
C_0	154.78	159.22	165.64	176.04	154.00
C_1	33.06	32.52	34.66	32.20	39.26
C_{s0}	148.58	149.68	142.14	146.34	156.06
C_{s1}	144.98	139.92	130.98	136.78	141.90
C_{w0}	79.60	80.18	76.14	78.40	83.60
C_{w1}	77.66	74.96	70.18	73.28	76.02
p_b	97.40	97.40	97.40	97.40	97.40
p_1	129.88	129.88	129.88	129.88	129.88
C_{p0}	325.58	327.28	315.7	322.14	337.06
C_{p1}	352.52	344.76	331.04	339.94	347.80
C_A	540.36	536.48	531.32	548.16	541.06
C_B	540.36	536.48	531.32	548.16	541.06
TB	13,451,482	13,700,554	14,104,270	12,886,782	13,393,672
TC	10,962,688	11,161,682	11,515,264	10,642,608	10,934,380
TNB	2,488,794	2,538,872	2,589,006	2,244,174	2,459,292

Note: Case 6: t_f increases 20%; Case 7: S_b increases 20%; Case 8: S_1 increases 20%; Case 9: t_0 increases 20 %; and Case 10: t_1 increases 20%.

Table 5 Sensitivity analysis for Regime II

	Case 1	Case 2	Case 3	Case 4	Case 5
P	699.92	495.74	594.52	569.22	557.08
Q_A	24,776	18,878	18,820	23,108	25,126
Q_B	7,400	5,434	5,572	6,728	7,326
V_A	16,088	12,258	12,222	15,006	13,596
V_B	4,806	3,528	3,618	4,368	3,964
C_0	137.8	117.92	141.64	118.82	123.02
C_1	31.64	29.82	35.76	29.88	30.30
C_{s0}	128.32	94.22	115.94	116.68	105.88
C_{s1}	130.70	99.58	119.14	121.90	110.46
C_{w0}	68.74	50.48	62.12	62.50	56.72
C_{w1}	70.02	53.34	63.82	65.30	59.18
p_b	97.40	97.40	97.40	97.40	81.16
p_1	129.88	129.88	129.88	129.88	108.22
C_{p0}	294.48	242.10	275.46	276.58	243.76
C_{p1}	330.60	282.80	312.84	317.08	277.86
C_A	500.04	430.52	490.24	465.78	431.16
C_B	482.28	410.02	467.10	445.40	416.78
τ_A	199.88	65.22	104.26	103.44	125.92
τ_B	217.64	85.74	127.40	123.84	140.30
TB	14,432,362	8,088,348	9,435,376	11,354,064	11,919,350
TC	9,321,540	6,399,896	7,137,220	8,102,678	8,165,966
TNB	5,230,822	1,688,452	2,298,156	3,251,386	3,753,384

Note: Case 1: a increases 20%; Case 2: b increases 20%; Case 3: μ increases 20%; Case 4: k increases 20 %; and Case 5: ρ increases 20%.

Table 5 Sensitivity analysis for Regime II (Continued)

	Case 6	Case 7	Case 8	Case 9	Case 10
P	578.60	575.70	571.06	583.90	579.06
Q_A	21,662	21,064	23,632	20,662	21,342
Q_B	6,156	7,376	5,810	6,014	6,376
V_A	14,066	13,678	15,346	13,416	13,858
V_B	3,998	4,790	3,772	3,906	4,140
C_0	124.78	126.30	128.98	146.68	124.54
C_1	30.50	30.32	31.16	30.22	36.48
C_{s0}	106.76	106.60	100.74	104.30	110.56
C_{s1}	114.26	111.12	103.88	109.00	112.58
C_{w0}	57.20	57.10	53.96	55.88	59.22
C_{w1}	61.22	59.52	55.66	58.40	60.32
p_b	97.40	97.40	97.40	97.40	97.40
p_1	129.88	129.88	129.88	129.88	129.88
C_{p0}	261.36	261.10	252.10	257.58	267.20
C_{p1}	305.36	300.52	289.42	297.26	302.76
C_A	460.62	457.14	449.56	474.16	463.78
C_B	446.14	437.4	431.08	454.26	441.72
τ_A	117.98	118.56	121.50	109.74	115.28
τ_B	132.46	138.30	139.98	129.66	137.34
TB	10,652,924	10,853,302	11,230,506	10,249,368	10,733,680
TC	7,584,740	7,695,910	7,985,588	7,487,076	7,579,632
TNB	3,068,184	3,157,392	3,244,918	2,762,292	3,034,048

Note: Case 6: t_f increases 20%; Case 7: S_b increases 20%; Case 8: S_1 increases 20%; Case 9: t_0 increases 20%; and Case 10: t_1 increases 20%.

Table 6 Sensitivity analysis for Regime III

	Case 1	Case 2	Case 3	Case 4	Case 5
P	700.50	495.56	594.62	569.32	556.68
Q_A	24,732	18,882	18,872	23,068	25,256
Q_B	7,322	5,474	5,498	6,750	7,284
V_A	16,060	12,262	12,254	14,980	13,666
V_B	4,754	3,554	3,570	4,382	3,942
C_0	137.34	117.98	141.60	118.78	123.18
C_1	31.62	29.82	35.78	29.88	30.32
C_{s0}	126.96	94.92	114.44	117.04	105.26
C_{s1}	130.46	99.60	119.46	121.68	111.02
C_{w0}	68.02	50.84	61.30	62.70	56.38
C_{w1}	69.90	53.36	64.00	65.18	59.48
p_b	318.18	181.82	227.28	220.78	221.86
p_1	331.16	194.80	233.76	233.76	232.68
C_{p0}	513.16	327.58	403.00	400.52	383.50
C_{p1}	531.52	347.78	417.24	420.64	403.18
C_A	700.50	495.56	594.62	569.32	556.68
C_B	700.50	495.56	594.62	569.32	556.68
TB	17,679,628	8,945,994	10,766,314	12,961,592	14,032,414
TC	12,448,986	7,257,570	8,468,258	9,710,222	10,279,136
TNB	5,230,642	1,688,424	2,298,056	3,251,370	3,753,278

Note: Case 1: a increases 20%; Case 2: b increases 20%; Case 3: μ increases 20%; Case 4: k increases 20%; and Case 5: ρ increases 20%.

Table 6 Sensitivity analysis for Regime III (Continued)

	Case 6	Case 7	Case 8	Case 9	Case 10
P	578.10	575.10	571.80	584.08	579.40
Q_A	21,700	21,152	23,536	20,620	21,212
Q_B	6,226	7,420	5,746	6,016	6,432
V_A	14,092	13,734	15,284	13,390	13,774
V_B	4,042	4,818	3,730	3,908	4,176
C_0	125.04	126.64	128.52	146.58	124.36
C_1	30.50	30.34	31.14	30.20	36.44
C_{s0}	107.96	107.24	99.64	104.34	111.52
C_{s1}	114.48	111.58	103.46	108.78	111.90
C_{w0}	57.84	57.46	53.38	55.90	59.74
C_{w1}	61.32	59.78	55.42	58.28	59.94
p_b	227.28	233.76	240.26	227.28	233.76
p_1	246.76	246.76	253.24	240.26	246.76
C_{p0}	393.06	398.46	393.28	387.5	405.04
C_{p1}	422.56	418.10	412.14	407.30	418.60
C_A	578.10	575.10	571.80	584.08	579.40
C_B	578.10	575.10	571.80	584.08	579.40
TB	12,362,670	12,641,228	13,038,040	11,763,854	12,265,062
TC	9,294,604	9,483,966	9,793,328	9,001,576	9,231,152
TNB	3,068,066	3,157,262	3,244,712	2,762,278	3,033,910

Note: Case 6: t_f increases 20%; Case 7: S_b increases 20%; Case 8: S_1 increases 20%; Case 9: t_0 increases 20%; and Case 10: t_1 increases 20%.

In case 2, an increase in the slope of demand (parameter b) means lower demand for a higher price. This generates an outcome which is the reverse of that in case 1, that is, a lower number of trips, lower marginal benefit, and lower average cost in each regime. This will induce a lower optimal congestion tax and a lower optimal parking fee. The total net benefit decreases due to the lower demand.

In case 3, as the value of time (parameter μ) increases, the average cost increases. This will induce lower demand and thus a lower number of equilibrium trips in regime A, and a lower number of optimal trips in regime B and in regime C. The marginal benefit increases due to the increase in cost in each regime. However, the optimal congestion toll and optimal parking fee decrease. This induces lower total net benefit.

In case 4, an increase in the road capacity per lane (parameter k) will lower the average cost and the marginal benefit for each regime. The number of equilibrium trips in regime A and the number of optimal trips in regime B and in regime C increase. The optimal congestion toll and optimal parking fee decrease. However, this induces higher total net benefit due to higher demand.

In case 5, an increase in vehicle occupancy (parameter ρ) denotes that more trips per vehicle are used. The average cost and marginal benefit for a trip decrease. This induces a larger number of equilibrium trips in regime A and a larger number of optimal trips in regime B and in regime C. However, the traffic volume in each regime decreases due to the higher vehicle occupancy. The optimal congestion toll and optimal parking fee decrease. However, this induces higher total net benefit due to higher trip demand. This case is beneficial to both individuals and the whole system. The users pay lower congestion fees in regime B and lower parking fees in regime C and yield higher net benefit. It also induces less congestion in the road system, which implies lower energy consumption and lower air pollution.

In case 6, an increase in the mass transit fee (parameter t_f) will increase the trip cost of modal alternative B. It thus decreases the number of trips by modal alternative B. This then induces a substitution effect of an increase in the number of trips by modal alternative A. The optimal congestion toll in modal alternative B decreases, while that in modal alternative A remains unchanged. The optimal parking fee is unchanged. This induces a decrease in the total net benefit.

In case 7, as the number of parking spaces in the surrounding city (parameter S_0) increases, the average cost of the trips by alternative B decreases. This induces an increase in the number of trips by modal alternative B and thus a decrease in the number of trips by modal alternative A via substitution effect. The optimal congestion toll in regime B increases while the optimal parking fee in regime C is unchanged. This induces an increase in the total net benefit.

In case 8, as the number of parking spaces in the center city (parameter S_1) increases, the average cost of the trips by alternative A decreases. This induces an increase in the number of trips by modal alternative A and thus a decrease in the number of trips by modal alternative B via substitution effect. The optimal congestion toll in regime B increases while the optimal parking fee in regime C remains unchanged. This induces an increase in the total net benefit.

In case 9, as the travel time in the surrounding city (parameter t_0) increases, the average cost of the trips by each modal alternative increases. This induces a decrease in the number of trips by each modal alternative in each regime. The optimal congestion toll in regime B decreases while the optimal parking fee in regime C stays unchanged. This induces a decrease in the total net benefit.

In case 10, as the travel time in the center city (parameter t_1) increases, the average cost of the trips by alternative A increases. This induces a decrease in the number of trips by modal alternative A and thus an increase in the number of trips by modal alternative A via substitution effect. The optimal congestion toll in regime B decreases while the optimal parking fee in regime C is unchanged. This induces a decrease in the total net benefit.

In addition, larger changes on the parameters in demand function are analyzed. The original values of parameter *a* and *b* are denoted by a_0 and b_0. The change up to 60% of the original value of the parameter *a* are used to evaluate the total net benefit, marginal benefit, total traffic trips, congestion tax, and additional parking charges (see Figure 1- Figure 5). The changes for parameter *b* are used to evaluate the same items in Figure 6- Figure10. Surprisingly, the total net benefit, marginal benefit, and total traffic trips in regime II and Regime III are still very close with larger changes on these two parameters.

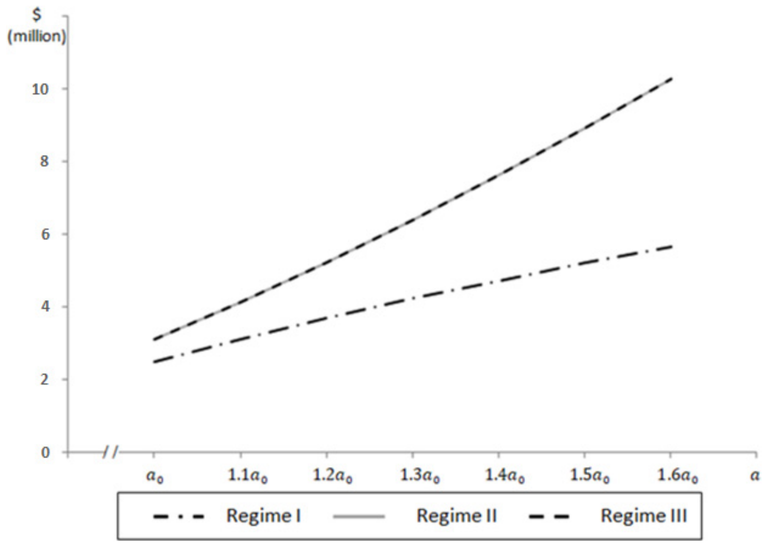

Figure 1 Total net benefit with various values of parameter *a*

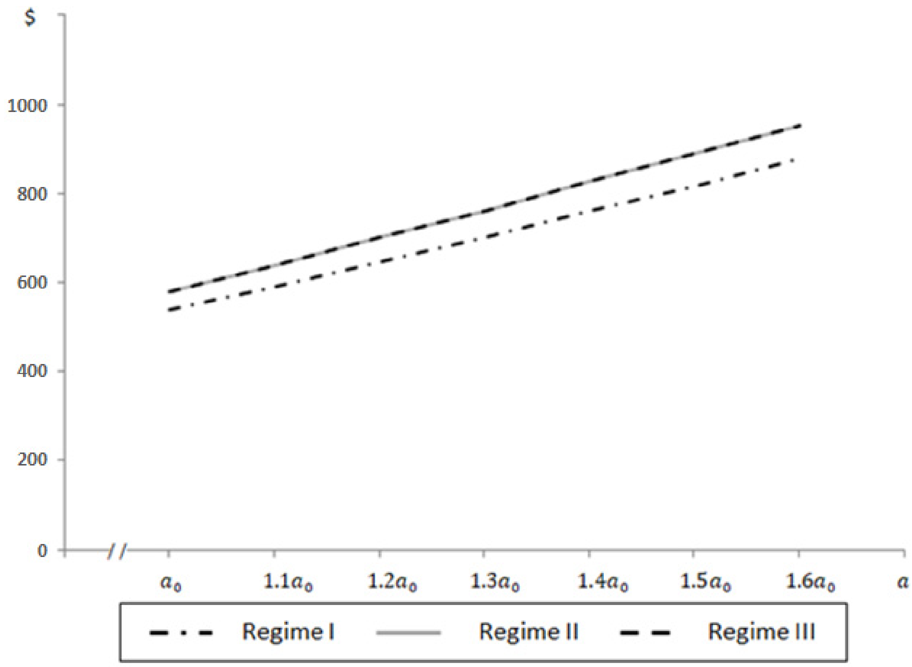

Figure 2 Marginal benefit with various values of parameter *a*

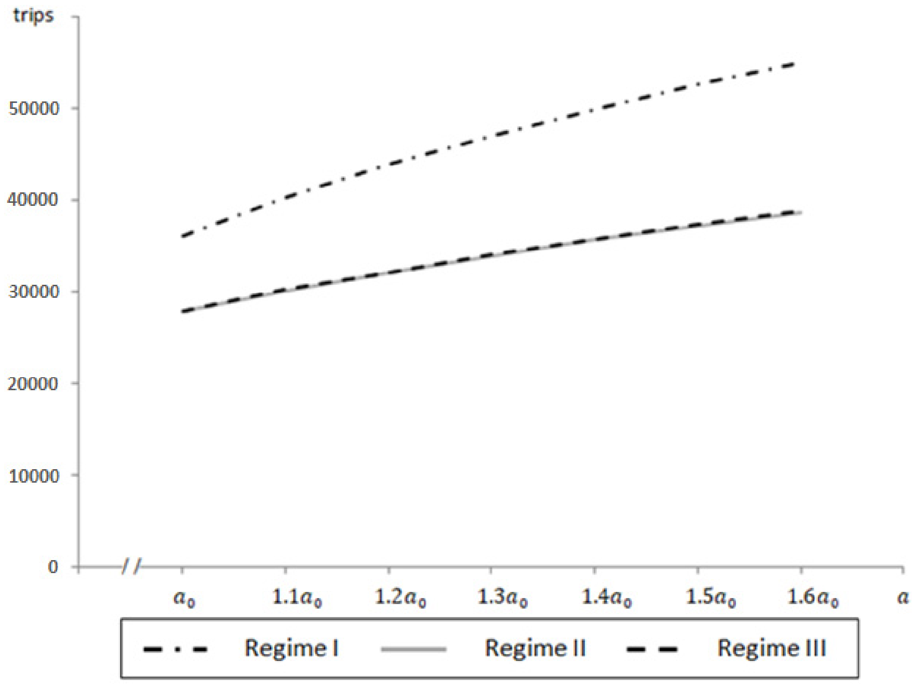

Figure 3 Total traffic trips with various values of parameter *a*

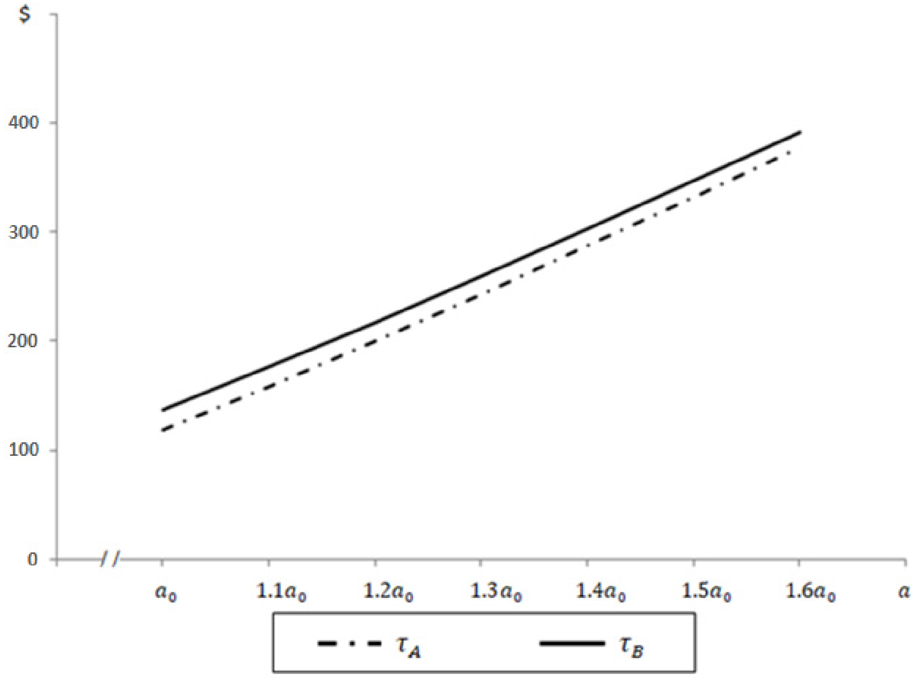

Figure 4 Congestion tax in Regime II with various values of parameter *a*

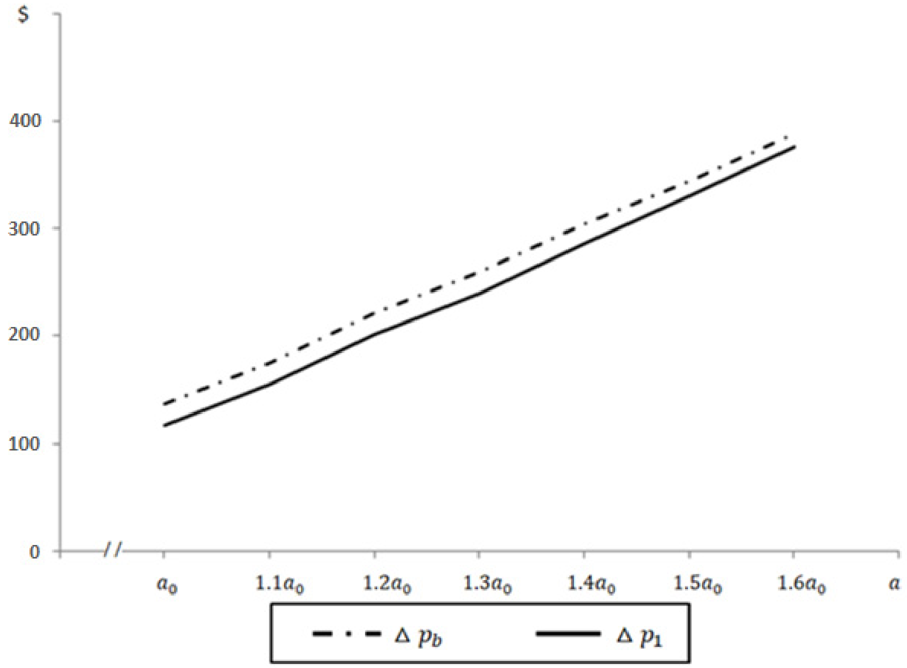

Figure 5 Additional parking charges in Regime III with various values of parameter *a*

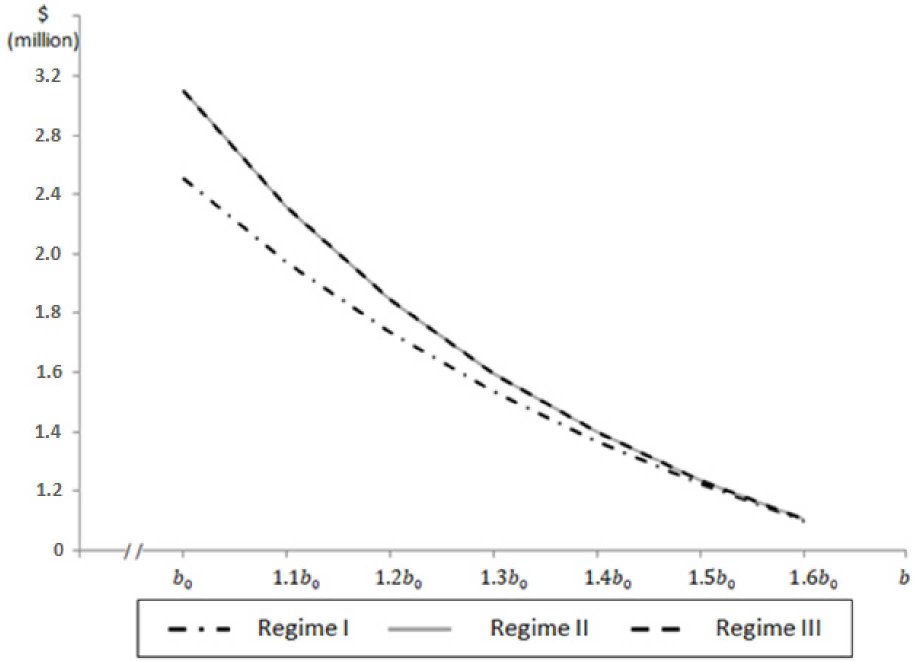

Figure 6 Total net benefit with various values of parameter *b*

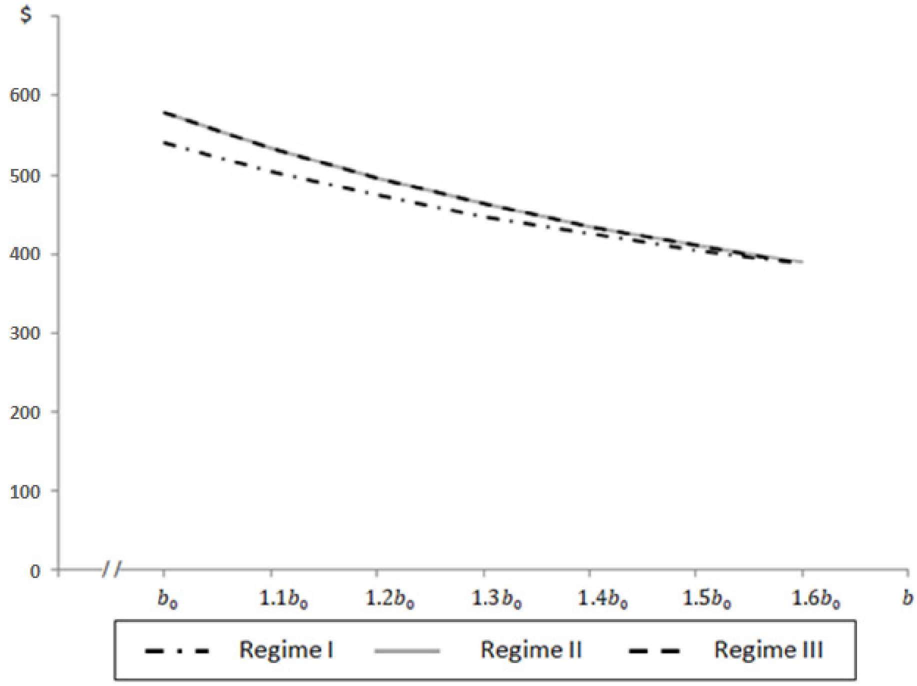

Figure 7 Marginal benefit with various values of parameter *b*

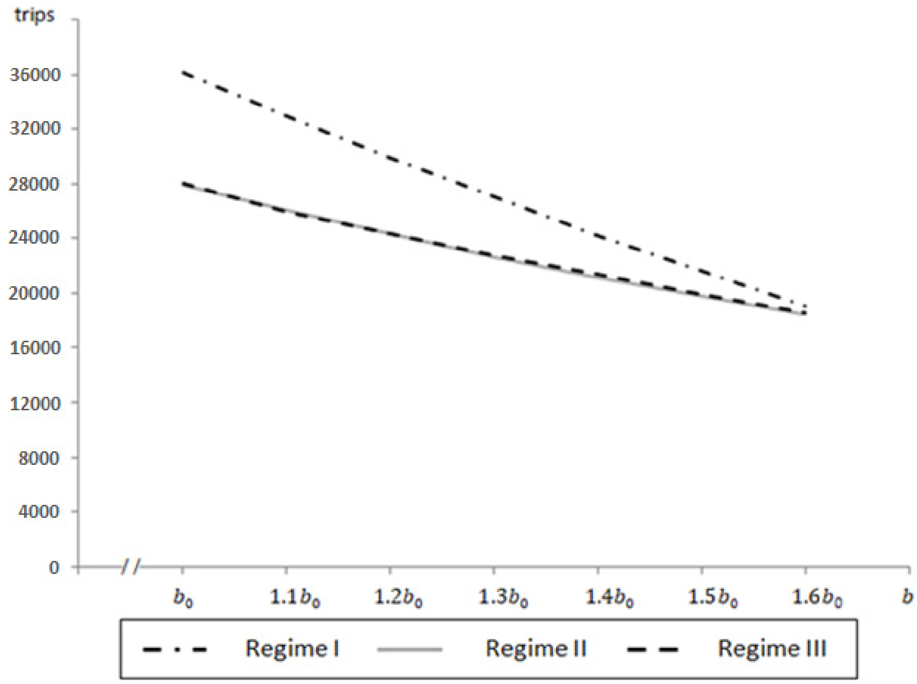

Figure 8 Total traffic trips with various values of parameter *b*

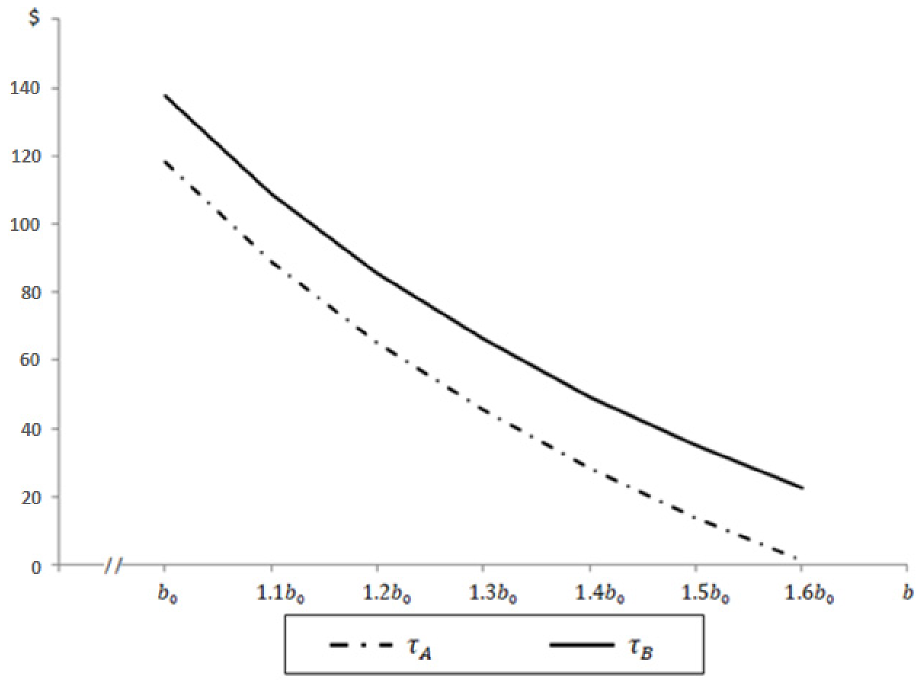

Figure 9 Congestion tax in Regime II with various values of parameter *b*

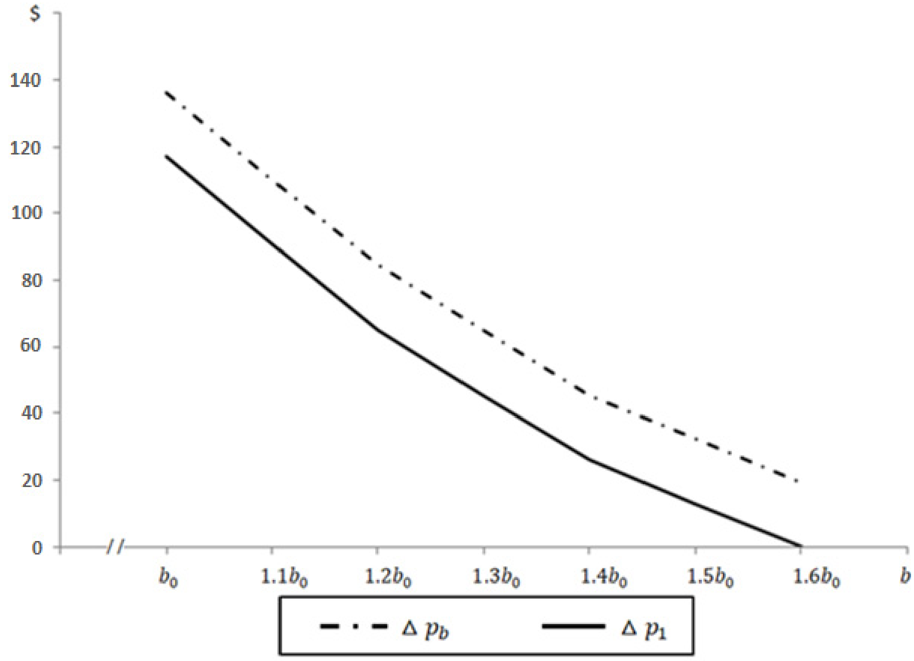

Figure 10 Additional parking charges in Regime III with various values of parameter *b*

V. Conclusions

This paper provides an approach to analyzing parking policy as a replacement for road congestion pricing tolls. The behavior of searching for a parking space is treated by an aggregate approach. Specifically, the time cost of searching for a parking space depends on the ratio of aggregate demand and aggregate supply in an area. Under the assumptions of a closed system with one road section, all the commuters have the same O-D pair and only one road to use. This approach provides an easier way to estimate the costs of searching for a parking space by the users with limited data available.

From a case study for the Taipei metropolis, it is found that the performance of optimal parking fee is close to the first-best optimum road pricing. However, it is noted that the result is reached under the condition that all the trips are with the same origin-destination pair and every trip needs parking. The former condition means all the trips incur the same external cost while the latter ensure the parking fee can be charged to every trip. In reality, the commuters may have multiple O-D pairs and multiple roads to use. However, the multiple O-D pairs can be simplified to an O-D pair without changing the effect on total net benefit as well as the congestion externality. In addition, multiple parallel roads with the same direction can be simplified to one road with the summation of all the trips and capacities of the multiple roads. However, a complicated network system may cause some different results. It is worth for future research.

In comparison with the first-best optimum congestion pricing which charges road users the exact external cost they generate, an optimal parking fee cannot differentiate between road users with different trip lengths. Specifically, the trips with different origin-destination pair will incur different congestion externality and thus a flat parking fee will not reflect the external cost for every trip. The policy of parking fee will thus cause a cross subsidy effect in which some road users are charged more than the external costs they generate, while others are charged less than the external costs they generate. This problem provides a direction for future research.

The behavior of searching for a parking space is complicated and itself generates extra external costs. Developing a more detailed model for the parking behavior of drivers may contribute a more plausible outcome for exploring the problem of lessening traffic congestion in an efficient way. This may be another issue for future research.

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Appendix A

1. The first-order conditions for maximizing the total benefit in Regime II are as follows:

$$\frac{\partial TNB}{\partial Q_A} = P \cdot \frac{dQ}{dQ_A} - (C_0 + C_1 + C_{s1} + C_{w1}) - Q_A \left(\frac{\partial C_0}{\partial V_A}\frac{dV_A}{dQ_A} + \frac{\partial C_1}{\partial V_A}\frac{dV_A}{dQ_A} + \frac{\partial C_{s1}}{\partial V_A}\frac{dV_A}{dQ_A} + \frac{\partial C_{w1}}{\partial V_A}\frac{dV_A}{dQ_A} \right) - Q_B \cdot \frac{\partial C_0}{\partial V_A}\frac{dV_A}{dQ_A} = 0, \tag{A1}$$

$$\frac{\partial TNB}{\partial Q_B} = P \cdot \frac{dQ}{dQ_B} - Q_A \frac{\partial C_0}{\partial V_B}\frac{dV_B}{dQ_B} - \left(C_0 + C_{s0} + C_{w0} + t_f \right) - Q_B \left(\frac{\partial C_0}{\partial V_B}\frac{dV_B}{dQ_B} + \frac{\partial C_{s0}}{\partial V_B}\frac{dV_B}{dQ_B} + \frac{\partial C_{w0}}{\partial V_B}\frac{dV_B}{dQ_B} \right) = 0. \tag{A2}$$

From some arrangements for the two equations above, the price (marginal benefit) for the two types of users are obtained as follows:

$$P = C_0 + C_1 + C_{s1} + C_{w1} + \frac{Q_A + Q_B}{\rho} \cdot \frac{\partial C_0}{\partial V_A} + \frac{Q_A}{\rho}\left(\frac{\partial C_1}{\partial V_A} + \frac{\partial C_{s1}}{\partial V_A} + \frac{\partial C_{w1}}{\partial V_A} \right), \tag{A3}$$

$$P = C_0 + C_{s0} + C_{w0} + t_f + \frac{Q_A + Q_B}{\rho} \cdot \frac{\partial C_0}{\partial V_B} + \frac{Q_B}{\rho}\left(\frac{\partial C_{s0}}{\partial V_B} + \frac{\partial C_{w0}}{\partial V_B} \right). \tag{A4}$$

Subtracting the RHS of (15) from the RHS of (A3) yields the congestion toll, τ_A, for type A of consumers in (21). Subtracting the RHS of (16) from the RHS of (A4) yields the congestion toll, τ_B, for type B of consumers in (22).

After employing the specific function forms for demand function in (27) and cost functions in (3)- (10), the first-order conditions and congestion tolls are as follows:

$$\frac{a}{b}-\frac{Q_A+Q_B}{b}=\mu\bar{t_0}\left[1+\alpha\left(\frac{Q_A+Q_B}{\rho K_0}\right)^{\beta}\right]+\mu\bar{t_1}\left[1+\alpha\left(\frac{Q_A}{\rho K_1}\right)^{\beta}\right]$$

$$+\mu\bar{t_s}\left(\frac{V_A}{S_1}\right)+\mu\left(\frac{d}{v}\right)\left(\frac{V_A}{S_1}\right)+\frac{Q_A+Q_B}{\rho}\mu\bar{t_0}\alpha\left(\frac{\beta}{K_0}\right)\left(\frac{Q_A+Q_B}{\rho K_0}\right)^{\beta-1}$$

$$+\frac{Q_A}{\rho}\mu\bar{t_1}\alpha\left(\frac{\beta}{K_1}\right)\left(\frac{Q_A}{\rho K_1}\right)^{\beta-1}+\frac{Q_A}{\rho}\left(\frac{\mu\bar{t_s}}{S_1}+\frac{\mu d}{VS_1}\right), \tag{A5}$$

$$\frac{a}{b}-\frac{Q_A+Q_B}{b}=\mu\bar{t_0}\left[1+\alpha\left(\frac{Q_A+Q_B}{\rho K_0}\right)^{\beta}\right]+\mu\bar{t_S}\left(\frac{V_B}{S_b}\right)+\mu\left(\frac{d}{v}\right)\left(\frac{V_B}{S_b}\right)$$

$$+t_f+\frac{Q_A+Q_B}{\rho}\mu\bar{t_0}\alpha\left(\frac{\beta}{K_0}\right)\left(\frac{Q_A+Q_B}{\rho K_0}\right)^{\beta-1}+\frac{Q_B}{\rho}\left(\frac{\mu\bar{t_s}}{S_b}+\frac{\mu d}{vS_b}\right), \tag{A6}$$

$$\tau_A=\frac{Q_A+Q_B}{\rho}\mu\bar{t_0}\alpha\left(\frac{\beta}{K_0}\right)\left(\frac{Q_A+Q_B}{\rho K_0}\right)^{\beta-1}+\frac{Q_A}{\rho}\mu\bar{t_1}\alpha\left(\frac{\beta}{K_1}\right)\left(\frac{Q_A}{\rho K_1}\right)^{\beta-1}$$

$$+\frac{Q_A}{\rho}\left(\frac{\mu\bar{t_s}}{S_1}+\frac{\mu d}{vS_1}\right)-\frac{p_1}{\rho}, \tag{A7}$$

$$\tau_B=\frac{Q_A+Q_B}{\rho}\mu\bar{t_0}\alpha\left(\frac{\beta}{K_0}\right)\left(\frac{Q_A+Q_B}{\rho K_0}\right)^{\beta-1}+\frac{Q_B}{\rho}\left(\frac{\mu\bar{t_s}}{S_b}+\frac{\mu d}{vS_b}\right)-\frac{p_b}{\rho}. \tag{A8}$$

The first-order conditions for the total net benefit in Regime III are as follows:

$$\frac{\partial TNB}{\partial p_b}=P\cdot\left(\frac{\partial Q_A}{\partial p_b}+\frac{\partial Q_B}{\partial p_b}\right)-\frac{dP}{dQ}\frac{\partial Q}{\partial p_b}(Q_A+Q_B)-P\cdot\left(\frac{\partial Q_A}{\partial p_b}+\frac{\partial Q_B}{\partial p_b}\right)$$

$$+\frac{p_1}{\rho}\frac{\partial Q_A}{\partial p_b}+\frac{p_b}{\rho}\frac{\partial Q_B}{\partial p_b}+\frac{Q_B}{\rho}=0, \tag{A9}$$

$$\frac{\partial TNB}{\partial p_1}=P\cdot\left(\frac{\partial Q_A}{\partial p_1}+\frac{\partial Q_B}{\partial p_1}\right)-\frac{dP}{dQ}\frac{\partial Q}{\partial p_1}(Q_A+Q_B)-P\cdot\left(\frac{\partial Q_A}{\partial p_1}+\frac{\partial Q_B}{\partial p_1}\right)$$

$$+\frac{p_1}{\rho}\frac{\partial Q_A}{\partial p_1}+\frac{p_b}{\rho}\frac{\partial Q_B}{\partial p_1}+\frac{Q_A}{\rho}=0. \tag{A10}$$

After some arrangements, these two equations are:

$$\frac{dP}{dQ}\frac{\partial Q}{\partial p_b}(Q_A+Q_B)=\frac{p_1}{\rho}\frac{\partial Q_A}{\partial p_b}+\frac{p_b}{\rho}\frac{\partial Q_B}{\partial p_b}+\frac{Q_B}{\rho}, \tag{A11}$$

$$\frac{dP}{dQ}\frac{\partial Q}{\partial p_1}(Q_A+Q_B)=\frac{p_1}{\rho}\frac{\partial Q_A}{\partial p_1}+\frac{p_b}{\rho}\frac{\partial Q_B}{\partial p_1}+\frac{Q_A}{\rho}. \tag{A12}$$