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A PRICING MODEL FOR HETEROGENEOUS PARKING DEMANDS[1]

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ABSTRACT

This paper explores monopoly pricing for heterogeneous parking demand with different parking time periods. Parking demands can be grouped as: short-time period and long-time period parking demands. The two types of demand will compete for a limited parking space and a fixed parking space. Part of the demanders that do not obtain parking at time i will continue searching for parking at time $i+1$. *The parking space available at time* $i+1$ *will be the sum of the leaving consumers at the beginning of this time period plus the space not being used as parking in pervious periods. The monopoly maximizes the profit accumulated by each time period. The result shows that the parking fees for the two groups of demands will be a combination of two pricing principles: "duration" based and "right" based pricing. The former charges the same amount of fee for every unit period and the latter charges the same fee for both groups of demands.*

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Key Words: *Parking fee; Heterogeneous demands; Monopolistic pricing*

I. INTRODUCTION

One of the biggest challenges facing urban areas is problem of parking, especially nearby and in Central Business Districts. Empirical studies emphasize on the impact of parking fees for travel behavior. [1] Theoretical models of parking markets explore the parking issue from several aspects. Lan (1987) presents an economic view of parking pricing and designs optimal parking price structures for different objectives subject to a parker's self-selection conditions. [2] Shoup and Willson (1990) use discrete choice econometric models to estimate the impacts of a change in parking policy through pricing policies. [3] Arnott *et al.* (1991) show that spatially-differentiated parking fees may rival time-differentiated congestion fees. [4] Arnott and Rowse (1999) present a parking congestion model focusing on drivers' search for a vacant parking space and show that a parking externality arises due to individuals' behavior. [5] Calthrop *et al.* (2000) show that pricing for parking and road use need to be simultaneously determined and show that the second-best pricing of all parking spaces produces higher welfare gains than the use of a single-ring cordon scheme. [6] Previous studies on parking pricing emphasize on the regulation of parking fees, parking funds, and parking demand management, and differentiating pricing for peak and non-peak or on different geographical locations. [7,8]4

This study explores monopoly pricing for heterogeneous parking demand with different parking time periods. For simplicity, two groups of parking demands are formulated: short-time period (one time period) and long-time period (two time periods) parking demands. The groups of demand will compete for a limited parking space. Part of the demanders that do not obtain parking at time i may continue searching for parking at time i+1. The parking space available at time period i+1 will be the sum of the leaving consumers at the beginning of this time period plus the space not being used as parking. This behavior will continue until the time window is closed. The focus of this paper is to answer the question that how the monopoly to set parking fees to maximize the profit accumulated for all of the time periods.

The rest of this paper addresses the structure of this paper as follows. Section 2 offers the detail of the theoretical model. Section 3 simulates the model in order to provide more insights

4. Lawrence Lan, Hsin-Li Chang, Yu-Sheng Chiang, and other researchers have focused on the parking behavior or parking demand models and have come out with fruitful results, but theirs is a different approach from this paper's point of view, and therefore the reviews of their results are omitted.

from the analytical solutions. Finally, brief concluding remarks appear in Section 4.

II. THE MODEL

This model describes the parking pricing behavior of a monopoly. We consider that there are k periods for parkers to park. Each period is assumed to be half an hour. These periods consist of peak periods and off-peak ones. To simplify the analysis, we assume that there are only two types of parkers: one for short-term parking (for one period) and one for long-term parking (for two periods).

A two-stage game is formulated to the problem. At stage 1, the monopoly sets a pair of prices for short-term parking and for long-term parking to maximize profit. At stage 2, consumers at each period decide whether to enter the parking market or not. We employ a backward induction approach for the problem to solve the equilibrium consumers in each period in stage 2 and then to solve the equilibrium prices of the firm in stage 1.

2.1 Consumers' Behavior

At every time period, there are two kinds of new potential parking demands that will compete for the available parking spaces. Terms $N_{i,s}$ and $N_{i,l}$ denote the new potential demands at period i for short-term and long-term parking, respectively.[5] The new potential parking demand means the demand at zero price. Therefore, we can expect that not all of this new potential demand will be demand for parking due to the pricing.

The new parking demand will compete for the available parking spaces depends on the parking fee at the beginning of period i are:

$N_{i,s} - b_s \times p_s$ for short-term demand, and

$N_{i,l} - b_l \times p_l$ for long-term demand.

Here, b_s and b_l are the slopes of the demand functions for short-term and long-term parking users. Furthermore, p_s and p_l are the parking fees set by the firm.

Aside from these new demands, another type of parker will enter this parking market to compete for parking space. This type of parker represents revisiting demand (residual demand from pervious time periods), $M_{i,j}$, that did not get a parking lot in the previous time periods. Equation (1) shows the total demand at period i. The term $d_{i,j}$ contains two parts: one is from

5. Since there are only k periods, the long-term parking demand, $N_{k-1,l} = 0$, is due to two-period parking.

the new demand, $N_{i,j}$, and the other is $M_{i,j}$. The demand function is given by:

$$d_{i,j} = N_{i,j} - b_j p_j + M_{i,j}\,, \quad i = 1, ..., k, \quad j = s, l \tag{1}$$

The third term of RHS in (1) represents the revisiting demand that can be expressed as $M_{i,j} = \overline{S}_{i-1,j} - b_j \tau$, where $\overline{S}_{i-1,j}$ is the parking demand of type j that did not get the parking space at period $i-1$.[6] This unsatisfied demand will revisit parking lots in the next time period if their willingness-to-pay is higher than the sum of the revisiting cost and the parking fee.[7]

Let S_i represent the total amount of available parking space at the beginning of period i, while $S_{i,j}$ represents the number of group j parkers who get parking space at period i, and $\overline{S}_{i,j}$ represents the number of group j parkers who want to park, but fail to get a parking lot at period i. Let L_i represent the parking space unoccupied at the end of period i. Therefore,

$$\begin{aligned} &\text{if } d_{i,s} + d_{i,l} \geq S_i\text{, then } L_i = 0\,. \\ &\text{if } d_{i,s} + d_{i,l} < S_i\text{, then } L_i = S_i - (d_{i,s} + d_{i,l})\,. \end{aligned} \tag{2}$$

The total amount of available parking space at the beginning of period i is $S_i = L_{i-1} + L_{i,s} + L_{i,l}$ where $L_{i,s}$ and $L_{i,l}$ denote the short-term and long-term demand with parkers in period $i-1$ who will leave (un-occupy) the parking lots at the beginning of period i. We assume that the probability of finding an available parking lot is independent on the user's style. There will be $d_{i,s} + d_{i,l}$ demand to compete for this availability; that is, the parking space occupied by j-type parkers is

$$S_{i,j} = S_i \times \frac{d_{i,j}}{\sum_j d_{i,j}}\,, \qquad \text{if } d_{i,s} + d_{i,l} \geq S_i \tag{3a}$$

or $\quad S_{i,j} = d_{i,j}\,, \qquad \text{if } d_{i,s} + d_{i,l} < S_i.$

The unsatisfied demand of j-type parkers is

$$\overline{S}_{i,j} = d_{i,j} - S_i \times \frac{d_{i,j}}{\sum_j d_{i,j}}\,, \qquad \text{if } d_{i,s} + d_{i,l} \geq S_i \tag{4a}$$

$$\text{or} \quad \overline{S}_{i,j} = 0\,, \qquad \text{if } d_{i,s} + d_{i,l} < S_i\,. \tag{4b}$$

6. If the firm sets the parking fees too low, then the demand for parking would be more than the total available parking lots, and therefore the unsatisfied demand may come back at the next period.
7. This revisiting cost, τ, includes the additional searching cost.

To describe the parking behavior for each period, we start from the first period. Assume that the total amount of available parking space is $\overline{S}$. Therefore, we know that $L_0 = \overline{S}$ and $L_{1,s} = L_{1,l} = 0$, $M_{1,s} = M_{1,l} = 0$. In the initial period, $d_{1,s}$ and $d_{1,l}$ are the demand to compete for all the available parking space, whereby only $S_{1,s}$ of short-term demand and $S_{1,l}$ of long-term demand get a parking space. The unsatisfied parking demand is $\overline{S}_{1,s} = d_{1,s} - S_1 \times \frac{d_{1,s}}{d_{1,s} + d_{1,l}}$ and $\overline{S}_{1,l} = d_{1,l} - S_1 \times \frac{d_{1,l}}{d_{1,s} + d_{1,l}}$ (we assume that $d_{1,s} + d_{1,l} \geq S_1$). The unoccupied parking space at the end of period 1 is zero; that is $L_1 = 0$.

At the beginning of the second period, there are $L_{2,s}$ of short-term parkers and $L_{2,l}$ of long-term parking demand that leave the parking space. We know that $L_{2,s} = S_{1,s}$ and $L_{2,l} = 0$ (because the long-term demand will park for two periods). Therefore, the total amount of available parking space for period 2 is only $S_2 = L_{2,s}$.

Following this induced process, we can easily obtain Eq. (5).[8] The available number of parking spaces S_i at period *i* is

$$S_i = L_i + L_{i,s} + L_{i,l} = L_i + S_{i-1,s} + S_{i-2,l} \quad \text{for} \quad i = 1, \ldots, k . \tag{5}$$

From Eqs. (3) to (5), we can find out the number of parkers for each type of demand under the firm's pricing strategy and demand characteristics. At the last period *k*, there is only the short-term parking demand since there is one period left. Figure 1 shows the process of parking demonstrated above.

2.2 Firm's Behavior

In stage 1 the firm will set a pair of uniform prices for short-term and long-term parking fees to maximize its profit. That is, the parking fee is not dependent on when to park, but only on how long they need to park. Therefore, there are two prices that a firm can set: p_s (price for half-hour parking) and p_l (price for one hour parking). The relationship between p_s and p_l is discussed as follows:

$$p_l \geq p_s \geq \frac{p_l}{2} . \tag{6}$$

We assume that the firm will not set a higher parking fee for short-term parking (one period) than the long-term (two periods) parking fee. Otherwise, the short-term parking parkers will stay longer and reduce to availability of parking space. On the other hand, we assume that if the parking fee for long-term parking (two periods) is greater than twice that of the short-term (one

8. We also assume that $S_{-1,l} = 0$ and $S_{0,l} = 0$ such that Eq. (5) will have a general form.

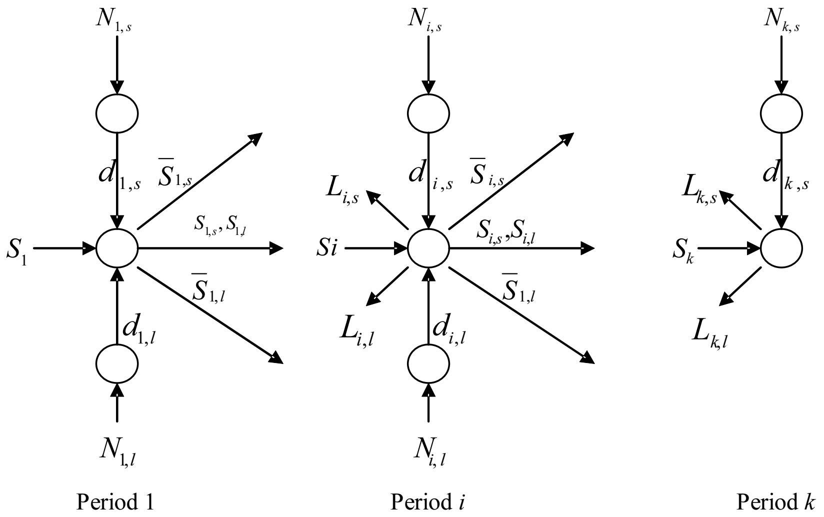

Figure 1　Consumers' Parking Process in Representative Periods

period) parking fee, then the long-term parkers will pay for their parking fee twice. This situation is also excluded. Therefore, Eq. (6) holds.

The cost function of the firm is assumed to have a constant marginal cost and is simplified to be zero. Therefore, the profit will equal the revenue from collecting the parking fees. The parking revenue summed up from time 1 to time k will be the total parking revenue. The price setting of the firm can thus be expressed as follows:[9]

$$\underset{p_s, p_l}{Max} \quad \sum_{i=1}^{k}[S_{i,s}(p_s, p_l)p_s + S_{i,l}(p_s, p_l)p_l] . \tag{7}$$

The first-order condition of the problem is:

$$\sum_{i=1}^{k}\left[p_s \frac{\partial S_{i,s}(p_s, p_l)}{\partial p_s} + S_{i,s}(p_s, p_l) + p_l \frac{\partial S_{i,l}(p_s, p_l)}{\partial p_s} \right] = 0 . \tag{8}$$

$$\sum_{i=1}^{k}\left[p_l \frac{\partial S_{i,s}(p_s, p_l)}{\partial p_l} + S_{i,l}(p_s, p_l) + p_l \frac{\partial S_{i,l}(p_s, p_l)}{\partial p_l} \right] = 0 . \tag{9}$$

9. Since $S_{i,j}$ is a function of $d_{i,j}$ (Eqs. (3a) and (3b)) and the $d_{i,j}$ is a function of p_j (Eq. (1)), therefore $S_{i,j}$ is a function of p_j. That is, $S_{i,s}$ and $S_{i,l}$ are all functions of (p_s, p_l).

Observing the LHS of (8), we find that increasing the short-term parking fee will result in three effects: the first term is the loss on short-term parking revenue incurred from a decrease on short-term parking demand; the second term is the gain on short-term revenue due to the price increase; the third term is the effect on long-term parking revenue that is normally positive due to the increase in long-term parking demand from the cross effect of the increase of short-term parking fee. Equation (9) has a similar meaning on the increase for a long-term parking fee.

The equilibrium short-term and long-term parking fees have to satisfy the condition that the sum of these three marginal effects be zero. That is, the negative marginal revenue (the first term) is equal to the positive marginal revenue (the second term and the third term) and the marginal revenue is zero. If the price is higher than the equilibrium price, then the marginal revenue is negative and the firm can decrease its price and lower the negative effect. If the price is lower than the equilibrium price, then the marginal revenue is positive and the firm can increase its price and enlarge the positive effect. Therefore, those prices satisfying the condition of marginal revenue being zero will represent the equilibrium solution.

III. SIMULATIONS

Due to the complexity of the model, we employ numerical simulations for further analysis. For simplicity, we assume that there are four periods only. Short-term parking will be for one period and long-term parking will be for two periods. To make the numerical analysis comparable, we set a benchmark case and show this benchmark as the first case in all the tables.

At the initial condition, there are 1,000 parking lots available; that is $\bar{S} = 1{,}000$. Period one and period four simulate the off-peak parking periods and period two and period three are peak parking periods. The potential demand during peak periods is assumed to be 1.2 times that in off-peak periods. The long-term parking demand in the fourth period is assumed to be zero, because there is only one period left for parking.

Let N_{so} and N_{lo} represent the new arrival potential demand of short-term and long-term parking during the off-peak time period, respectively.[10] We assume that $N_{so} = 600$, meaning that the new potential short-term demand for off-peak periods (periods 1 and 4) is 600 and for peak periods (periods 2 and 3) is 720. We also assume that $N_{lo} = 1{,}000$, meaning that the new potential long-term demand in period 1 is 1,000 and in periods 2 and 3 it is 1,200.

The slopes of the demand function for short-term and long-term parking are both 1. The

10.This means that $N_{1,s} = N_{s0}$, $N_{1,l} = N_{l0}$, $N_{2,s} = 1.2\,N_{s0}$, $N_{2,l} = 1.2\,N_{l0}$, $N_{3,s} = 1.2\,N_{s0}$, $N_{3,l} = 1.2\,N_{l0}$, $N_{4,s} = N_{s0}$, and $N_{4,l} = 0$.

revisiting costs are 60 for both revisit demands. The decision for a firm, as we mentioned, is p_s and p_l; in other words, the parking fees to maximize a firm's revenue. The result of the analysis on this benchmark is shown in the first column of Table 1. This benchmark case shows that the ratio of short-term parking fee to long-term parking fee is 0.5. The revenue for this case is 1,156,224.

Table 1 also shows other cases with various potential demands from the long-term group. When the potential demand of long-term group changes from 1,000 to 550, the associated parking fees and total revenue are obtained. We find that as the potential arrival demand decreases, the ratio of short-term and long-term parking fees changes from 0.5 to 1 and a firm collects a less amount of total revenue (TR). The trends of the long-term and short-term parking fees and the ratio of these two parking fees are shown in Figure 2.

Table 1　The Parking Fees with Different Potential Demand from the Long-Term Group

$\bar{S}$	1000	1000	1000	1000	1000	1000	1000	1000
N_{so}	600	600	600	600	600	600	600	600
N_{lo}	1000	900	800	750	700	650	600	550
b_s	1	1	1	1	1	1	1	1
b_l	1	1	1	1	1	1	1	1
τ	60	60	60	60	60	60	60	60
p_s	384.00	371.05	393.81	380.90	373.69	363.81	353.72	346.67
p_l	768.00	664.48	623.09	569.55	513.16	458.09	403.14	346.67
Fee Ratio	0.5000	0.5584	0.6320	0.6688	0.7282	0.7942	0.8774	1.0000
TR	1,156,224	1,050,298	949,389	904,428	859,289	813,864	768,189	722,222

Note that when N_{lo} decreases from 1,000 to 550, p_l steadily decreases from 768.00 to 346.67, but p_s decreases from 384.00 to 371.05, then jumps to 393.81 and decreases again to 346.67. The reason is that the decrease from the potential demand results in a change on the relationship between demand and supply from 3(a) to 3(b) and this causes the unexpected jump of p_s.

Table 2 shows the cases with various potential demand from the short-term group. When the potential demand of the short-term group increases from 600 to 1,300, the associated parking fees, total revenue, usage rate, and reject rate are obtained. The results of this case just show another direction of those in Table 1. We find that in this situation when the potential arrival of short-term demand increases, the ratio of short-term and long-term parking fees changes from

0.5 to 1, but the firm collects a larger amount of total revenue (TR). The explanation for the unexpected jump in p_l is similar to that from a jump of p_s in Table 1. The trends of the long-term and short-term parking fees and the ratio of these two parking fees are shown in Figure 3.

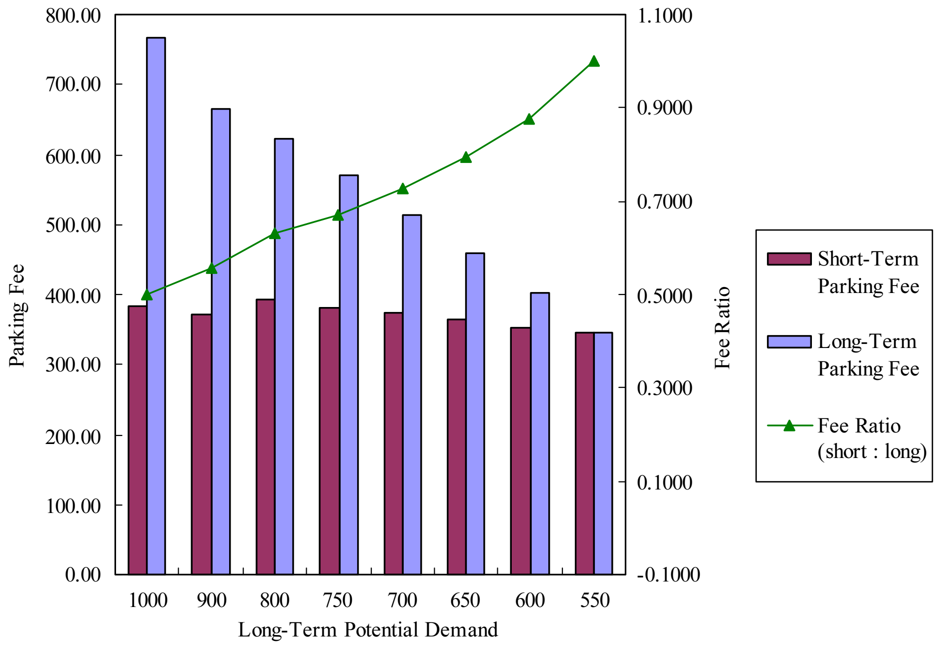

Figure 2 The Trends of the Parking Fees and Ratios with Different Potential Demand From the Long-Term Group

Table 2 The Parking Fees with Different Potential Demand for the Short-Term Group

$\bar{S}$	1000	1000	1000	1000	1000	1000	1000	1000
N_{so}	600	700	800	900	1000	1100	1200	1300
N_{lo}	1000	1000	1000	1000	1000	1000	1000	1000
b_s	1	1	1	1	1	1	1	1
b_l	1	1	1	1	1	1	1	1
τ	60	60	60	60	60	60	60	60
p_s	384.00	456.81	514.07	523.76	596.75	688.26	754.51	830.14
p_l	768.00	791.60	822.96	709.18	722.53	744.98	794.16	830.14
Fee Ratio	0.5000	0.5771	0.6247	0.7386	0.8259	0.9239	0.9501	1.0000
TR	1,156,224	1,274,739	1,412,470	1,576,459	1,775,488	1,986,940	2,215,469	2,456,867

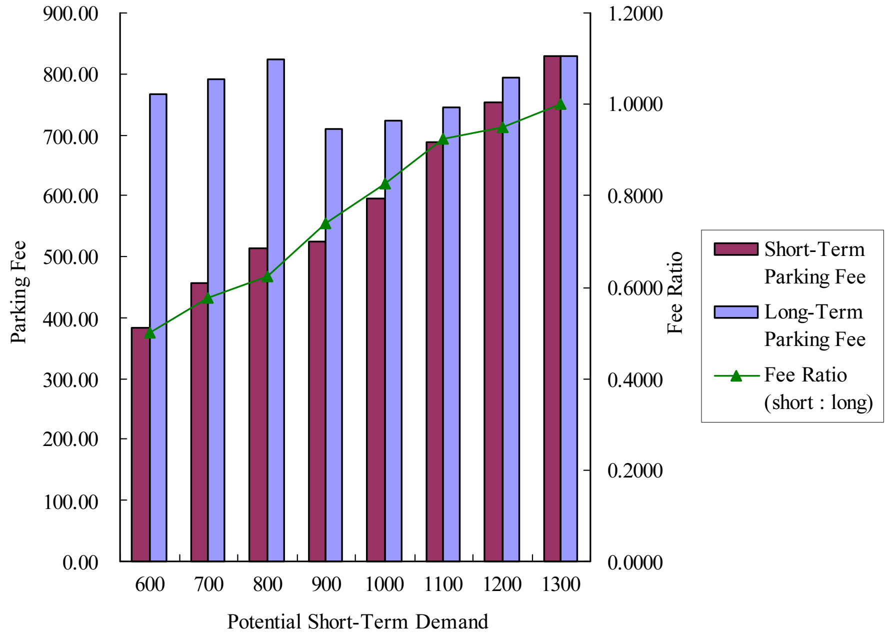

Figure 3　The Trends of the Parking Fees and Ratios with Different Potential Demand for the Short-Term Group

To understand the impacts from the characteristics of demand, we analyze the sensitivity of the slope of the demand function. Table 3 shows the cases with various slopes of the long-term demand function. When the slope of the long-term group, b_l, changes from 1 to 2.5, the associated parking fees, total revenue, usage rate, and reject rate are obtained. When b_l increases the firm will raise the ratio of the parking fee and will receive less revenue. As b_l is small (1), the firm will charge the same fee for one period's worth of parking regardless of whether demand is short term or long term. That is, long-term parkers pay twice the parking fee of the short-term parkers just because they park for two periods. In other word, the parking fee is based on the duration of parking.

When b_l becomes larger (say, 2.5), the firm will charge the short-term and long-term parkers the same parking fee regardless of how long (or how short) they park. That is, short-term parkers and long-term parkers pay the same fee for the "right" to park. For those with $b_l = 1.5$ and $b_l = 2$, the parking fee can be regarded as a combination of the "duration" and "rights" based pricing mechanism. The trends of the long-term and short-term parking fees and the ratio of these two parking fees are shown in Figure 4.

Table 4 shows the cases with various revisiting costs from 60 to 10. When the revisiting cost decreases, the ratio of the short-term parking fee and the long-term parking fee increase and the revenue increases. The trends of the long-term and short-term parking fees and the ratios of these two parking fees are shown in Figure 5.

Table 3 The Parking Fees with Different Slope Coefficients of the Long-Term Demand Function

$\bar{S}$	1000	1000	1000	1000
N_{so}	600	600	600	600
N_{lo}	1000	1000	1000	1000
b_s	1	1	1	1
b_l	1	1.5	2	2.5
τ	60	60	60	60
p_s	384.00	366.80	356.56	353.33
p_l	768.00	517.73	390.86	353.33
Fee Ratio	0.5000	0.7085	0.9122	1.0000
TR	1,156,224	905,800	781,851	698,422

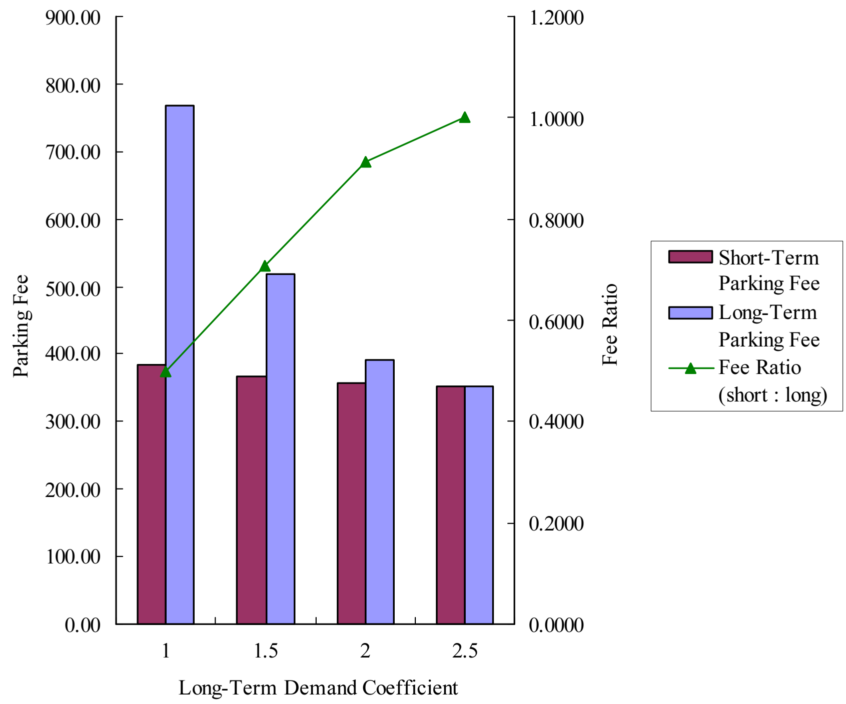

Figure 4 The Trends of the Parking Fees and Ratios with Different Slope Coefficients of the Long-Term Demand Function

Table 4　The Parking Fees with Various Revisiting Costs

$\bar{S}$	1000	1000	1000	1000	1000	1000
N_{so}	600	600	600	600	600	600
N_{lo}	1000	1000	1000	1000	1000	1000
b_s	1	1	1	1	1	1
b_l	1	1	1	1	1	1
τ	60	50	40	30	20	10
p_s	384.00	386.14	387.38	388.44	389.36	391.60
p_l	768.00	766.93	766.31	765.78	765.32	764.20
Fee Ratio	0.5000	0.5035	0.5055	0.5072	0.5088	0.5124
TR	1,156,224	1,160,089	1,163,958	1,167,837	1,171,726	1,175,621

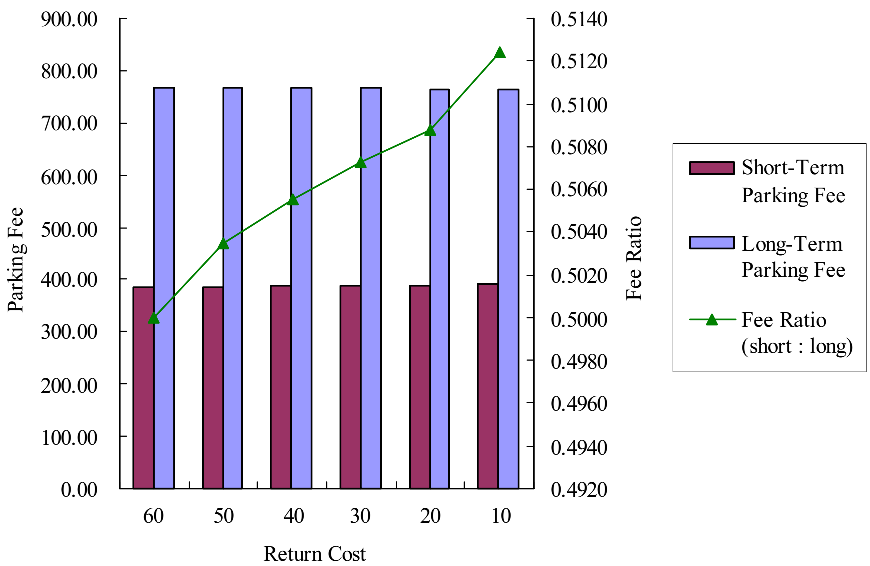

Figure 5　The Trends of Parking Fees and Ratio with Various Revisiting Costs

Table 5 shows the cases with various parking lots from 1,000 to 1,800. When the number of parking lots increases, the ratio of the short-term parking fee and long-term parking fee rises. The trends of the long-term and short-term parking fees and the ratios of these two parking fees are shown in Figure 6.

Table 5 The Parking Fees with Increasing Total Parking Space

$\bar{S}$	1000	1200	1400	1600	1800
N_{so}	600	600	600	600	600
N_{lo}	1000	1000	1000	1000	1000
b_s	1	1	1	1	1
b_l	1	1	1	1	1
τ	60	60	60	60	60
p_s	384	388.4412	370.9361	338.2666	330
p_l	768	765.7794	674.5319	590.8667	566.6666
Fee Ratio	0.5000	0.5072	0.5499	0.5725	0.5824
TR	1,156,224	1,266,334	1,357,326	1,396,903	1,398,933

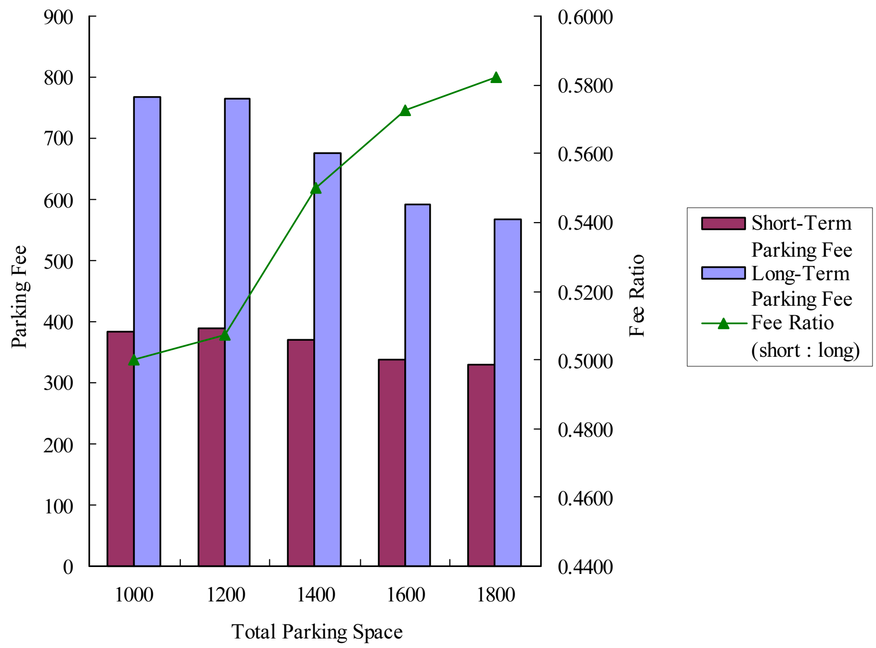

Figure 6 The Trends of Parking Fees and Ratios with Increasing Total Parking Space

IV. CONCLUSIONS

This paper explores a model for parking pricing with multiple time periods. Our model considers revisiting parking demand and peak/off-peak periods. The principal results of our analysis are that the parking fee would be charged on the basis of “duration” or on the “right” of parking. “Duration” based parking means that the parkers pay the same fee for every unit period. Therefore, the long-term parkers pay twice the short-term parkers because the long-term parkers “consume” two time periods and short-term parkers only “consume” one period. “Right” based parking pricing means that both short-term and long-term parkers pay the same parking fee; that is, regardless the parking duration, the long-term parkers pay the same amount of parking fee as the short-term parkers even the long-term parkers “consume” twice the parking periods. We find that the “duration” based parking pricing will be applied when the slope of long-term demand is small. In contrast, the “right” based parking pricing is applied when the slope of long-term demand is large or the total amount of parking space is large. Therefore, this model provides an explanation to the various parking pricing policies.

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