Estimating congestion toll by using traffic count data — Singapore’s area licensing scheme

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Abstract

There are many studies on the Area Licensing Scheme in Singapore. One of the debatable issues is whether or not the congestion toll of $3 is too high. The main objective of this paper is to develop a simple method for estimating the congestion toll by directly using the commonly available traffic count data. In our sensitivity analysis, we use three different scenarios on the choice of the value of travel time savings and four different measures of average wage rates (the national average wage rate, the average wage rate for car owners with or without taking into consideration of employment benefits, and the average wage rate per car derived from the average occupancy per car). The sensitivity analyses led to a general conclusion that by 1990, the $3 fee was not too high. We also highlight the fact that it is possible to iterate to the optimal congestion toll by comparing the theoretical congestion toll with the actual toll even when the demand curve is unknown. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The Area Licensing Scheme (ALS) in Singapore has been in operation since June 2, 1975. It is a cordon road pricing system consisting of a restricted zone (RZ) in the city area originally with twenty-two vehicular entry points, later expanded to twenty-eight entry points. The RZ includes the whole of the Central Business District (CBD) and the commercial areas of Chinatown as well as that portion of the Orchard Road shopping corridor up to Scotts Road. The original objective of the early ALS was to discourage the widespread use of private cars for commuting purposes to the CBD during morning peak hours (7:30–10:15 AM) to relieve congestion. Drivers and taxis were required to purchase and display an area licence to enter the RZ. Other vehicles and car pools were exempted from the restriction.

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In June 1989, the scheme was revised with a new objective, which was to charge all vehicles using the road at times and at places when and where they cause congestion. By December 1989, the restrictions were extended to the evening peak hours and to all vehicles except buses and emergency vehicles.\(^2\)

Since 1994, the restrictions were further extended for the whole day from 7:30 AM to 6:30 PM, which is known as the Whole-day Area Licensing Scheme (WALS). The off-peak hours are 10:15 AM to 4:30 PM for weekdays and before 2:00 PM on Saturdays. All vehicles, except for the exempted categories, entering into the RZ during the peak hours must pay $3 per day or $60 per month.\(^3\) During off-peak hours, motorists will have to pay $2 per day or $40 per month. Company cars are charged double. As an immediate result of WALS, the traffic has become smoother and the congestion experienced right after 10:15 AM and just before 4:30 PM has been considerably reduced.

In early 1997, a formal road pricing scheme (RPS) was implemented on three major expressways during the morning peak hours with a $2 charge.\(^4\) To avoid any confusion resulting from different peak hours at expressways and inside the CBD, the peak hours were standardized, namely, morning peak hours are from 7:30 to 9:30 AM and afternoon peak hours are from 4:30 to 7:00 PM. This initiative was to facilitate the transition to the upcoming Electronic Road Pricing (ERP) scheme to be activated in April 1998.

Not surprisingly, there is a general consensus in the literature that having been in operation for more than two decades, the ALS has proven to be quite effective in reducing and containing the congestion problem in the city area during peak hours. It was also quite cost effective and flexible. On the other hand, several studies have been questioned the validity of the congestion toll charged and the welfare impact of the scheme. Toh (1977) was the first attempt to investigate whether $3 was the correct congestion toll in 1975 and concluded that it was too high on the grounds that a traffic reduction of 87% was way out of the original target of 25–30%. Wilson (1988) brought up the associated welfare issues. Using data in later 70s, he concluded that the early ALS led to welfare losses to commuters.

McCarthy and Tay (1992) was another attempt to obtain estimates for congestion toll, which was based on the traffic count data collected in 1990 – the same data used in the present paper. Their conclusion was that the $3 charge was still too high in 1990. Their analysis, although methodologically correct, suffers an important shortcoming. They used the average national wage rate and a very conservative value of travel time savings when estimating the congestion toll. This is potentially misleading because the average Singaporean family did not own a car.

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\(^2\) When first implemented in 1989, the evening restricted hours were from 4:30 to 7:00 PM. Due to problems encountered by parents picking up school children in the restricted zone, the evening restricted hours were changed to 4:30–6:30 PM in early 1990. The government indicated that schools in CBD should be relocated. By 1997, only one private school was still inside CBD. For more comprehensive discussions on ALS, refer to Menon and Lam (1992, 1993).

\(^3\) All dollars in the paper are in Singapore Dollar, which is roughly equal to US $0.61 in February 1998.

\(^4\) Initially, those who had a valid ALS licence did not need to pay when travelling on expressways. But the traffic condition on the Central Expressway (CTE), which basically handles the traffic from Northern area of the island to CBD, did not see any improvement after the RPS. It was found that majority of peak-hour drivers on CTE are ALS Licence holders. To improve the condition on CTE, an additional $2 fee was imposed during the morning peak hours.
The aim of this paper is to develop a simple model to check how close to the optimum is the current congestion toll for the ALS. It does this based only on the traffic count data by using the average wage rate of car owners and taking into consideration of new evidence on the value of time savings. Even though Singapore’s ALS has been replaced by a much sophisticated and automated ERP system, we believe that the present study is still valuable because a cordon road pricing system has the potential to be implemented in many major cities in the world (either manually or electronically) and it is very important to have a simple method to check whether or not the congestion toll charged is reasonable.

The rest of the paper is organised as follows. Section 2 discusses the survey data used in this paper, but the primary focus is on the development of methodology in estimating the congestion toll by using the traffic count data. In Section 3, we provide the theoretical congestion toll estimates under various scenarios related to different values of time and traffic conditions. It will also discuss the convergence issue of the theoretical congestion toll and actual congestion toll. Section 4 is the conclusion.

2. Methodology

The data for this study is a traffic survey undertaken by the Public Works Department (PWD) in the RZ in February 1990. The information consists of the in-bound and out-bound traffic counts by the time of the day, as well as travelling times along two fixed routes within the RZ. The survey found that the average number of vehicles per lane per hour in the RZ was 450 per lane during the period when the ALS was in operation and 600 per lane during the period when the ALS was not in operation.

Two fixed arterial road circuits, A and B, were established within the RZ for the survey, with Circuit A measuring 7.166 km long and Circuit B measuring 6.663 km long. There were 31 intersections (1 was unsignalized) in Circuit A and 32 intersections (all signalized) in Circuit B. These two circuits are considered as representative of the general traffic conditions in the RZ, as they cover most of the major roads inside the RZ.

In order to capture a wider variation in the traffic volumes and speeds, the survey was conducted over three days of the week: Friday, Saturday and Sunday. Ten cars were used to actually drive and chase in the two circuits during the two periods – ALS in operation and ALS not in operation. Each car had made about 16 round trips a day. A total of 511 trips were made during the entire three days of the survey. The total inbound and outbound traffic volumes were counted at the entry points of the two circuits during these hours of the experiment, which were used to derive the average traffic volume per lane per hour.

The average speed was higher and the average intersection delay was lower during the peak period on both of the circuits (see Table 1) due to the effect of ALS. This is consistent with the

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5 Since September 1995, the road related functions of PWD had been merged into the Land Transport Authority (LTA), which also included the Registry of Vehicles (ROV), the Mass Rapid Transit (MRT) and urban transport department under the Ministry of Communications. LTA now becomes the sole government agency to plan and develop urban transport infrastructures and to manage all urban transport issues.
The results mentioned earlier that the average number of vehicles was 450 and 600 during the periods when the ALS was and was not in operation, respectively.

The rest of this section derives a simple congestion toll estimation formula that is based on traffic count data as in Table 1.

The concept of road pricing can be traced back to Pigou (1920) who argued that road users should be taxed because they cause congestion. Fig. 1 shows the marginal social cost (MC) and average social cost (AC) curves associated with the use of a particular stretch of road. An individual driver entering the road will only consider the costs that he bears personally and he will ignore congestion costs that he imposes on the other road users. Consequently, the AC curve is equivalent to the new road user’s marginal private cost curve, that is, the additional costs borne by the new road user himself (Walters, 1961). The MC curve relates to the marginal social costs for the new and existing road users as a result of the addition of the new road user to the road.

In Fig. 1, at traffic volume below $Q_1$, vehicles can flow freely at the level of speed limit. Since an additional motorist will not impede the traffic flow, MC is the same as AC at traffic volumes up to $Q_1$. Beyond $Q_1$, an additional motorist will impede other motorists and slow down the traffic. Since the marginal private cost is increasing after the traffic volume $Q_1$ (i.e., AC is increasing), the MC should lie above the AC for every additional driver beyond the traffic volume $Q_1$. It is well-known that $Q_3$ is the market equilibrium and $Q_2$ is the socially optimal flow. To attain the socially optimum level of traffic volume $Q_2$, the congestion toll is the difference between MC and AC at $Q_2$, which is $(B - A)$. Since the marginal social cost curve is given by $MC(x) = AC(x) + x \times dAC(x)/dx$, therefore congestion toll is given by $CT = x \times dAC(x)/dx$.6

In the case of ALS, since we only have two observations, we can only use the first-order differential on the AC curve in the estimation of the congestion toll, that is,

$$CT = x \frac{\Delta AC}{\Delta x} = x \frac{AC_{\text{non-ALS}} - AC_{\text{ALS}}}{x_{\text{non-ALS}} - x_{\text{ALS}}},$$

where,

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Table 1

<table>
<thead>
<tr>
<th>Road characteristics</th>
<th>Circuit A</th>
<th>Circuit B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (km)</td>
<td>7.166</td>
<td>6.663</td>
</tr>
<tr>
<td>Number of intersections</td>
<td>31</td>
<td>32</td>
</tr>
<tr>
<td><strong>Average journey speed (km/hr)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALS</td>
<td>27.6</td>
<td>23.3</td>
</tr>
<tr>
<td>Non-ALS</td>
<td>20.3</td>
<td>16.8</td>
</tr>
<tr>
<td><strong>Average intersection delay (s)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALS</td>
<td>7.4</td>
<td>9.9</td>
</tr>
<tr>
<td>Non-ALS</td>
<td>11.5</td>
<td>16.6</td>
</tr>
</tbody>
</table>


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6 There is an enormous amount of literature in the road pricing. For a more in-depth discussion on the theory of road pricing, for example, refer to Walters (1961) and Hau (1992).
ACALS the average cost during the ALS period, ACnon-ALS the average cost during the non-ALS period, xALS, the traffic level during the ALS period, which is 450, xnon-ALS, the traffic level during the non-ALS period, which is 600.

It is well-known that the AC curve can be assumed to be proportional to travel time. That is, we have 
\[ AC(x) = \frac{d}{V} \times c, \]
where \( d \) is the distance travelled (km), \( V \), the vehicle speed on the road (kilometers per hour), and \( c \) the generalized travel cost per hour ($). Note that \( \frac{d}{V} \) is the total travelling time, which consists of the moving time (the actual driving time) and the waiting time (the total time stopped at intersections). Empirical evidence suggests that drivers value the moving time differently from the waiting time at the intersections (Hensher, 1989). As a result, AC can be represented as
\[ AC(x) = T_w(x)c_w + T_m(x)c_m, \]
where \( T_w(x) \) and \( T_m(x) \) are the total waiting time and total moving time at the traffic level \( x \), respectively, and \( c_w \) and \( c_m \) are the hourly generalized travel cost for the waiting state and moving state respectively. As a common practice, we will represent the hourly generalized travel cost as a percentage of the wage rate, that is, \( c_w = \delta_w \omega \) and \( c_m = \delta_m \omega \), where \( \omega \) is the average wage rate.

Under the above setting, it follows immediately that
\[
CT = \frac{\Delta AC}{\Delta x} = \frac{(T_{w,\text{non-ALS}}\delta_w + T_{m,\text{non-ALS}}\delta_m)\omega - (T_{w,\text{ALS}}\delta_w + T_{m,\text{ALS}}\delta_m)\omega}{x_{\text{non-ALS}} - x_{\text{ALS}}} x \]
where \( T = \) time; \( \delta, \) value of time as a percentage of average wage rate; \( \omega, \) average wage rate; \( m, \) the moving state of the driving; \( w, \) the waiting state of the driving; \( \text{ALS, the ALS period; non-ALS, the non-ALS period.} \)

Using the data in Table 1, we can compute the total travel time and the total waiting time under both the ALS and the non-ALS periods for each circuit. The results of these computations are summarised in Table 2. Substituting travel time values into the congestion toll formula, we obtain the following expressions for the congestion tolls on circuit \( A \) and circuit \( B \):

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7 Refer to Walters (1961), p. 687.
With these expressions, we can get the theoretical congestion toll estimate at a given traffic flow \( x \) once the values of \( \omega, \delta_m \) and \( \delta_w \) are given.\(^8\)

### 3. Congestion tolls estimates and sensitivity analysis

In order to estimate the congestion toll, we must have some information on the values of the parameters \( \delta_w, \delta_m \) and \( \omega \). Let us start with the average wage rate \( \omega \). Three possible values will be considered here. The first one is the national average wage rate in 1990, which is $7.58 per hour (denoted as \( \omega_1 \) in Table 3).\(^9\) The second one is the average wage rate of car owners based on the 1990 national census data, which indicated that the average monthly income for car owners was $2,931. Assuming that on average people work for 44 h per week and given that there are \( 4.3333 = 52/12 \) weeks in a month, the total number of working hours in a month will be \( 4.3333 \times 44 = 190.67 \) h. Thus, the average wage rate of the car owners is $2,931/190.67 = $15.37 per hour (denoted as \( \omega_2 \) in Table 3).

Note that in Singapore employers are required to contribute to employee’s Central Provident Fund (CPF) account, which was about 18.5% of the salary in 1990.\(^10\) In addition, there is an year-end bonus that is on average about two months of salary plus CPF contribution. After taking into account of these employment benefits, the implied monthly income is $4,052.11 (about 38.25% higher than the normal monthly income). This is translated into the average wage rate of $21.51 (denoted as \( \omega_3 \) in Table 3).

\(^8\) Readers are reminded that the theoretical congestion toll depends on MC and AC and is increasing with the traffic volume; while the actual congestion toll depends on AC and the demand curve and is decreasing with traffic volume. These two converge only when MC intersects the demand curve as illustrated in Fig. 1.

\(^9\) McCarthy and Tay’s result (McCarthy and Tay, 1992) was based on this figure.

\(^10\) Currently, the CPF contribution is 20% of the salary subject to a ceiling.
In calculating the third value for the wage rate, we will use the average wage rate per car. According to a study by Centre for Transportation Studies (1993), the average car occupancy is 1.43. Based on the 1990 census data (Singapore Census of Population, 1990), the average monthly income for car passengers was $2,255, which was translated as $11.83 hourly wage. Therefore after adjusting CPF contribution and annual bonuses, the average hourly wage rate per car is given by $(15.37 + 0.43 \times 11.83) \times 1.3825 = $28.28 (denoted as \omega_4 in Table 3).

Using \omega_1 may be misleading, an understated wage and value of time will underestimate the optimal congestion toll. On the other hand, using \omega_4 may cause outcry from the public on the basis that these people driving alone will certainly feel it unfair, which will make the government reluctant to use this wage rate (\omega_4) due to the potential political risk involved. Therefore, the sensible choice is either \omega_2 or \omega_3.

As for the values of \delta_w and \delta_m, we must rely on the empirical studies on the value of travel time savings. Using 1975 data, Wilson (1988) has estimated that the value of travel time in Singapore ranged between 47–49% of the wage rate. Hence as a base case, we will first estimate the congestion toll for the combination (\delta_w, \delta_m) = (0.5, 0.5), which is also the case used by McCarthy and Tay (1993). We call this Scenario 1.

According to a recent study by Png et al. (1994), the value of time for private car owners in Singapore was found to be about 67% of the average wage rate. So our Scenario 2 is the combination (\delta_w, \delta_m) = (0.67, 0.67). To further capture the fact that \delta_w is generally greater than \delta_m, we decide to use (\delta_w, \delta_m) = (0.75, 0.67) as the Scenario 3 as part of our sensitivity analysis. The choice of \delta_w = 75% is indeed a bit of arbitrary due to lack of empirical study in Singapore’s context; but it is probably safe to say that it is not too high considering the empirical evidence in Sydney of Australia (Hensher, 1989). In our view, Scenarios 2 and 3 are more realistic than Scenario 1.

The congestion toll estimates under three scenarios for the three choices of the wage rate \omega are summarised in Table 3 below. Before discussing the congestion toll estimates, it is important to note that all estimates in Table 3 are the theoretical congestion toll, which is why the estimate is increasing in the flow level (because the difference between MC and AC is increasing with traffic volume). The actual toll, which is the difference between the demand curve and the AC curve, must be decreasing with traffic volume. The common dilemma is that the demand curve is usually unknown and difficult to estimate. But this does not imply that it is impossible to check whether the actual toll charged is reasonable or optimal. In fact, to check whether the actual toll, which is $3 in our case, is optimal, we only need to check whether the theoretical congestion toll is equal to $3 at the observed traffic flow level, which is 450. If the theoretical congestion toll is higher than the actual toll ($3), it implies that the actual toll is too low. By increasing the actual toll, the observed traffic volume will fall, which will lead to a decrease in the theoretical congestion toll at the new observed traffic level. The reverse argument can be made when the theoretical congestion toll is lower than the actual toll.

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11 Hensher (1989) studied the value of travel time savings (VTTS) for car commuters in Sydney and found that the VTTS is about 68% of the wage rate. In addition, he also found that the VTTS for waiting time is about 84% of the wage rate.

12 Mohring et al. (1987) reported that the value of travel time savings for bus commuters is in the range of 60% to 120% of the average wage rate. For more information on VTTS, refer to Waters (1992) and Waters (1995).
toll is lower than the actual toll. This adjustment process will guarantee the convergence of the theoretical congestion toll and the actual toll so long as the government is willing to do so. Furthermore, this adjustment process will enable the government to infer the demand curve over a limited range of traffic levels that is relevant to road pricing. Unfortunately, the actual toll in Singapore has been quite static over the years.

We now comment the congestion toll estimates in Table 3. It is evident that when the national average wage rate ($\omega_1 = 7.58$) is used, all the congestion toll estimates at the traffic level between 450 and 600 are less than the $3 fee under all three scenarios. When the average car owner’s wage rate ($\omega_2 = 15.37$) is used, the congestion toll estimates at the observed traffic level of 450 (during the peak hours) for Circuit A are $2.15, 2.89, 4.04$ under the three scenarios, respectively, whereas those for Circuit B are $2.55, 3.42$ and $3.64$ respectively. If we take the average the two estimates under Scenario 2 and the wage rate $\omega_2$ (probably the least objectionable case), the congestion toll is about $3.15$. If we use the average per car wage rate adjusted for the employment benefits ($\omega_3 = 21.51$), the congestion toll estimates at the flow of 450 for Circuit A are $3.01, 4.04, 4.22$ under the three scenarios respectively, whereas those for Circuit B are $3.57, 4.78$, and $5.09$, respectively, which are all greater than the actual toll of $3 charged. Note that even under the Scenario 1, the congestion tolls are in fact higher than $3 on both circuits. Similar observations can be made when the average wage per car ($\omega_4 = 28.28$) is used. With these, we probably can conclude that the $3 licence fee was not too high in 1990. In fact, it was on the low side.

Table 3
Congestion toll–estimates and sensitivity analyses

<table>
<thead>
<tr>
<th>Flow</th>
<th>$\omega_1$ (A)</th>
<th>$\omega_2$ (A)</th>
<th>$\omega_3$ (A)</th>
<th>$\omega_4$ (A)</th>
<th>$\omega_1$ (B)</th>
<th>$\omega_2$ (B)</th>
<th>$\omega_3$ (B)</th>
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<tr>
<td>400</td>
<td>0.94</td>
<td>1.91</td>
<td>2.68</td>
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<tr>
<td>450</td>
<td><strong>1.06</strong></td>
<td><strong>2.15</strong></td>
<td><strong>3.01</strong></td>
<td><strong>3.96</strong></td>
<td><strong>1.42</strong></td>
<td><strong>2.89</strong></td>
<td><strong>4.04</strong></td>
<td><strong>5.31</strong></td>
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<td>500</td>
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<td>3.35</td>
<td>4.40</td>
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<td>4.17</td>
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<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
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</thead>
<tbody>
<tr>
<td>$\delta_w = 0.5, \delta_m = 0.5$</td>
<td>$\delta_w = 0.67, \delta_m = 0.67$</td>
<td>$\delta_w = 0.75, \delta_m = 0.67$</td>
</tr>
<tr>
<td>Flow</td>
<td>$\omega_1$</td>
<td>$\omega_2$</td>
</tr>
<tr>
<td>------</td>
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</tr>
<tr>
<td>400</td>
<td>1.12</td>
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</tr>
<tr>
<td>650</td>
<td>1.82</td>
<td>3.68</td>
</tr>
</tbody>
</table>

$\delta_w$: the value of waiting time in percentage of wage; $\delta_m$: the value of moving time in percentage of wage; $\omega$: the wage rate (all in S$).
4. Conclusion

In this paper, we have addressed one of the most controversial issues related to Singapore’s ALS, that is, whether the $3 license fee was too still high. Previous studies have claimed that the $3 was indeed too high. As demonstrated in this paper, when the wage rate for car owners is used to link to the value of time savings, rather than use the national average wage rate, the congestion price estimates are quite close to the actual $3 license fee. In fact, there is evidence that $3 is on the low side. Nevertheless, with findings in this paper, it seems difficult to argue that $3 is too high. By using the traffic count data that can be collected easily, we have derived a formula for estimating the theoretical congestion toll in terms of the average wage rate, the value of waiting time and the value of moving time. This is very flexible for policy makers and transport planners. As long as they have accurate information on these parameters, they can calculate the correct road price. In fact, this is the main purpose of this paper.

Fully realizing that without knowing the demand function, it is very hard to argue whether any particular road price is optimal. In fact, the theoretical congestion toll estimates in Table 3 are irrelevant to the demand curve. On the other hand, the actual congestion toll ($3 in our case) only depends on the average social cost curve and the (unknown) demand curve and does not depend on the marginal social cost curve. By noting the fact that the theoretical congestion toll and the actual toll converge only when the traffic volume is at the socially optimal level, the government is able to “find” the correct amount of toll to charge so long as there is an adjustment process in the actual toll. This adjustment process will also be useful in deriving the demand curve for a limited range of traffic levels that is relevant to road pricing.

Singapore’s experience in road pricing should be useful to other countries. But the political dimension of road pricing usually makes it much more difficult to implement. From policy makers’ point of view, it ultimately leads to two very tricky issues. The first one is the welfare issue and the other one is the redistributional issue. To make Singapore’s ALS useful to other countries, it is critical to demonstrate that the system has in fact improved social welfare. Wilson’s (Wilson, 1988) study had drawn a negative conclusion on the welfare effect of ALS. A more updated and comprehensive welfare analysis on ALS warrants further research.

Readers are reminded that the methodology developed in this paper is more applicable for a cordon RPS, like the ALS in Singapore. The main reason is that since many vehicles entering the cordon may stay inside for the whole day, it is probably difficult to implement any congestion toll system that depends on either the distance traveled, or time duration inside the cordon, or the entry-exit combination, or the number of entries only. The daily licence with the distinction of the peak-period and off-peak-period seems to be more practical and less objectionable by those who may perceive the system unfair.

On the other hand, for road pricing on expressways, it is possible to develop a congestion toll system that is distance- and time-based. Since the speed-flow relationship in expressways is very different from the speed-flow relationship on the city business district, the congestion toll estimation for the CBD is not directly applicable to expressways even though the methodology may still be valid. The traffic mixture in the expressways is much more diverse than these in the CBD area. A majority of the trips heading to the CBD during the peak hours are commuting or working trips, which justifies using the average wage rate of the working drivers when estimating the congestion toll. But on the expressways, a substantial portion of the traffic consists of light
goods vehicles and heavy trucks, in which case both the driver and the vehicle are considered to be part of the “production” process. It will certainly underestimate the value of the travel time savings if only the wage rate of the driver is used. This will substantially complicate the matter. To obtain accurate congestion toll estimates on expressways, it is critical to have accurate operating cost models for various vehicles as well as value of travel time savings estimates for various vehicles types and trip purposes.

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