Congestion Pricing for Air Pollution Reduction—Environmental Evaluation of Pollution-Adjusted-Rate Pricing and Comparison with Other Strategies

by

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Abstract

Congestion pricing is expected to have a positive impact on air pollution since it reduces traffic congestion, which is a significant cause of air pollution in most urban areas. This study investigates the impact of congestion pricing on emissions of hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) through a macroscopic simulation.

Reviews of the theory and current developments of congestion pricing are described. Although practical implementation has been limited to a small number of cities, economic theory and supporting toll-collection technologies have been well developed. The impact of road transportation on air pollution is then described.

As the main objective of congestion pricing is to reduce the level of congestion, air pollution reduction is usually considered as a byproduct. However, greater air pollution reduction is possible if the pricing scheme is modified to include air pollution reduction as another main objective. Such a pricing scheme, named "pollution-adjusted-rate congestion pricing", is proposed in this study. This pricing scheme forces "dirty" vehicles out of congestion by charging higher amounts of tolls on them.

The air pollution effects of congestion pricing and other policies, such as reducing numbers of old vehicles, reducing the overall demand, and introducing zero-emission vehicles (ZEV), are simulated. The computer model used in the simulation employs a constant elasticity named "avoidance elasticity" and a probability function named "willingness-to-shift function" to simulate users' time-shifting behavior, which is not negligible in the case of congestion pricing.

The simulation results show the positive effects of congestion pricing policies on air pollution reduction; in particular, they show that pollution-adjusted-rate pricing achieves greater reduction compared to ordinary congestion pricing.

The simulation model can be used in the initial stages of the planning process as a preliminary means of evaluating a congestion pricing policy.

Thesis Supervisor: Joseph M. Sussman
Title: JR East Professor of Civil and Environmental Engineering

Thesis Reader: Ralph Gakenheimer
Title: Professor of Urban Planning and of Civil and Environmental Engineering

Acknowledgments

After adding his signature to this thesis, Prof. Sussman, the thesis supervisor, drew a figure as shown below and said, "This is what your progress curve has to be like (the straight line), and yours was something like this (the bottom curve)."

As this comment illustrates, my slow progress at the beginning caused a big hustle at the end. First of all, I would like to thank Prof. Sussman for his valuable comments and advice despite the hustle. His cordial smile and severe comments worked as carrots and sticks to motivate a lazy person like me to work on this thesis. There is no doubt that I would have had to waste the deposit for the commencement gown rental without his patience and appropriate guidance.

The same is true of the thesis reader, Prof. Gakenheimer. He gave me well-directed advice, and I often appreciated his prompt responses when he went through my drafts.

My friends at MIT and other schools have contributed in both the slow progress at the beginning and the rapid progress towards the end. I could not have survived in the environment full of genius and hard-working people without their support. I appreciate all the people who played tennis, volleyball and other sports with me and who spent their time with me for their friendship.

One thing I tend to forget but thank the most is the financial support from the Japanese government. My study at MIT has been sponsored by the Ministry of Construction and the National Personnel Authority.

One more thing I often take for granted and tend to forget to be thankful to is the support from my parents and sister. As my sponsor did not allow me to go back to my home country during the two-year stay in the United States, they visited me last summer and brought me great encouragement. Now, I wish my sister for a happy marriage as she is getting married in September.

Reflecting this invaluable experience, I hope, in the future, to become able to get things done, as Prof. Sussman pointed out, following the straight line in the figure below.

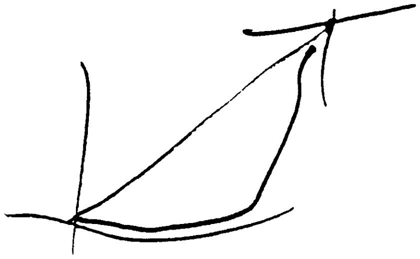

Figure 0: Expected and real progress curves

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Abbreviations

ALS Area Licensing Scheme

AVI Automatic Vehicle Identification

BPR Bureau of Public Roads

CARB California Air Resources Board

CBD Central Business District

CIF Cost, insurance, and freight

CO Carbon monoxide

COE Certificate of Entitlement

DOC Department of Commerce

DOT Department of Transportation

ENP Electronic number (license) plate

EPA Environmental Protection Agency

ERP Electronic Road Pricing

ETC Electronic Toll Collection

FHWA Federal Highway Administration

FR Federal Register

FRT First registration tax

FTA Federal Transit Administration

FTP Federal test procedure

GAO General Accounting Office

GDP Gross Domestic Product

HC Hydrocarbon

HDDT Heavy-duty diesel-powered trucks

HDGV Heavy-duty gasoline-powered vehicles

HK$ Hong Kong dollar

HOV High occupancy vehicles

I&M Inspection and maintenance

ISTEA Intermodal Surface Transportation Efficiency Act

ITS Intelligent Transportation Systems

LAX Los Angeles Airport

LDDT Light-duty diesel-powered trucks

LDDV Light-duty diesel-powered vehicles

LDGT Light-duty gasoline-powered trucks

LDGV Light-duty gasoline-powered vehicles

LEV Low Emission Vehicle

LOS Level of service

MC Motorcycles

mi Mile(s) (=1.6 km)

mph Miles per hour (speed)

MRT Mass Rapid Transit

MTC Metropolitan Transportation Commission

NAAQS National Ambient Air Quality Standards

NO_2 Nitrogen dioxide

NO_x Oxides of nitrogen

O_3 Ozone

OECD Organization for Economic Co-operation and Development

Pb Lead

pcphpl Passenger cars per hour per lane (traffic volume)

PM-10 Fine particulate matter less than 10 microns

S$ Singapore dollar

SCF Speed Correction Factor

SO_2 Sulfur dioxide

SOV Single occupancy vehicles

SR State Route

TDM Transportation Demand Management

TRB Transportation Research Board

TSP Total suspended particulate matter

TTI Texas Transportation Institute

UMTA Urban Mass Transportation Administration

VMT Vehicle miles traveled

VOC Volatile organic compounds

vph Vehicles per hour (traffic volume)

ZEV Zero Emission Vehicle

Chapter 1

Introduction

1.1 What is congestion pricing?

The Metropolitan Expressway in Tokyo is notorious for its heavy traffic, which lasts almost all day in some parts of the city. Drivers sometimes complain, "Since the expressway is no faster than untolled streets, toll charges should be refunded when it is heavily congested." Also, some people say, "The expressway is so congested that nobody wants to use it."

The first statement is exactly the opposite to the concept of congestion pricing. According to the theory of congestion pricing, higher tolls should be charged when the road is heavily congested. What is the logic behind the theory?

If we look at the second complaint, we see that it implies that the negative effects of congestion—mainly time loss—impose disincentives to use the facility during congested periods. If these disincentives are great enough and "nobody" uses the facility, there would not be any congestion and everybody would be happy all the time. Therefore, the existence of congestion suggests that this disincentive is not great enough to eliminate the problem.

Because the disincentive for drivers is not great enough to force them to avoid congested highways, congestion pricing must make up the difference when drivers make decisions about their trips. Drivers' decisions do not depend on "everybody's happiness", or social costs but on the driver's own happiness, or private costs that are significant only to him or her (internal costs). Therefore, by charging appropriate amounts of additional tolls during hours of congestion, one can achieve a situation in which people would say, "The toll is so expensive that only the appropriate number of people will want to use it."

1.2 Idea of Pollution-Adjusted-Rate Congestion Pricing

Saving road users' time on traveling is not the only benefit of congestion reductions. Air pollution reduction is also one of the benefits that congestion reductions bring about. As the primary goal of congestion pricing is congestion reduction, it is expected to produce some air pollution benefits as well.

In this thesis, one form of congestion pricing scheme, named "pollution-adjusted-rate congestion pricing", will be proposed. This pricing scheme attempts to more actively reduce air pollution—not as a byproduct of congestion reduction—by charging different amounts of tolls depending on vehicles' pollution characteristics. "Dirty" vehicles, or vehicles with high levels of emissions, such as heavy-trucks and old vehicles, would be charged with higher tolls than "cleaner" vehicles during peak periods. Under this pricing scheme, emission reductions beyond the level that can be reached by ordinary congestion pricing could be achieved because it changes not only the peak characteristics of traffic volume but also the vehicle composition of peak and non-peak periods.

Although the overall emission reduction may bring a social benefit as a whole, a social benefit of each individual, or more specifically, of each income group, may not increase. An issue of equity—who are better-off or worse-off after the policy—would be one of the most serious concerns about this pricing scheme as dirty vehicles, especially old vehicles, are often owned by the poor. This issue will not be examined in detail in this thesis as it includes complex political issues like the use of revenues. However, it requires careful considerations when it is applied in practice.

Some of vehicle characteristics, such as vehicle age or fuel type, which have strong impact on emission levels may not be physically visible from outside, but it is necessary to be able to identify those characteristics at toll booths in order to charge different amounts depending on them. Unlike manually-operated toll booths, automatic vehicle identification (AVI) technology is capable of identifying those kind of information if they are stored in tags mounted on each vehicle. This technology provides great opportunity for highly variable pricing schemes like pollution-adjusted-rate congestion pricing. Descriptions on AVI and related technologies will be given in Chapter 2.

1.3 Thesis Overview

In this thesis, the impact of congestion pricing policies on air pollution will be discussed. The idea of congestion pricing is not new, and its economic theory is well established. However, its practical application is limited to a small number of cities in the world, and its impact on air pollution is mostly unknown. The economic theory of congestion pricing and its applications will be explained in Chapter 2. Recent developments in toll collecting technologies and current movements in the United

States since the Intermodal Surface Transportation Efficiency Act (ISTEA) will then be introduced.

Besides congestion, air pollution is another major source of externalities associated with road transportation. Chapter 3 will explain how road transportation is causing negative effects on the environment and how the government has dealt with its problem. Also, an emission estimate model to be used in the simulations in Chapter 5 will be introduced.

The primary goal of congestion pricing is to reduce congestion, and road users benefit from congestion reductions by saving their time on their trips. Congestion reductions also bring air pollution benefits, and the impact of congestion pricing on air pollution has been studied. Chapter 4 proposes a pricing scheme named "pollution-adjusted-rate congestion pricing", which is designed to more actively reduce air pollution by a pricing policy—not merely as a byproduct of congestion reductions. Under this pricing scheme, different amounts of tolls would be charged depending on the emission levels of vehicles, and additional emission reductions beyond the level achieved by ordinary congestion pricing schemes are expected to be achieved.

To compare the emission impacts of various policies described in previous chapters, a series of simulations will be run in Chapter 5; and emission reductions to be expected from the application of each policy will be presented. Also, the level of efforts, across various policies, required to achieve the same emission reduction levels will be presented as "iso-impact" lines.

Finally, Chapter 6 will present policy implications and conclusions.

Chapter 2

Congestion Pricing

2.1 Overview

Congestion pricing or peak-period fees is a widely accepted practice in many industries. People are accustomed to paying different prices for the same goods or services depending on when they are consumed. For example, long-distance phone calls are normally cheaper in the early morning than in busy work hours. Electricity is supplied at a lower rate during the night in most countries although the United States uses a flat or block rate price structure.

This type of demand-adjusted pricing is also used in the transportation industry. Airplane tickets are usually priced higher when the level of demand is high. In the United Kingdom, peak-period pricing has been introduced for airport runways although none of the airports in the United States have adopted such a pricing scheme[23]. Regarding transit, more than 30 transit systems in the United States have introduced time-of-day pricing in which adult fares vary by time on weekdays. These systems include a number of different transit modes such as bus, rapid rail, and dial-a van, and cities ranging in population from fewer than 25,000 to over 4 million[5, 6].

In this chapter, congestion pricing theory and applications in the field of road transportation will be reviewed. Although "pollution-adjusted-rate congestion pricing", which will be introduced in Chapter 4, will not be included in this chapter, some of the theory and technologies introduced in this chapter are directly applicable to it.

In spite of the limited number of practical application, the theory of congestion pricing in the field of road transportation has been well developed. A brief description of the economic theory will be given in Section 2.2.

Recent technical developments in toll collecting equipment is making implementation of even more complex pricing schemes possible at a low cost. Technical developments and operational design options will be reviewed in Section 2.3.

Despite the promising economic theories and supporting technical developments, the application of congestion pricing to road transportation is limited to a small number of cities in the world. In the United States, the Congress created the Congestion Pricing Pilot Program in 1991 under the Intermodal Transportation Efficiency Act (ISTEA), and several pilot projects are underway. The experiences and current movements in the United States and other countries will be described in Section 2.4.

The main stumbling block for practical application of congestion pricing, so far, has been political concerns that charging drivers for using roads, previously untolled, would hamper the regional competitiveness in production, or put too heavy a burden on the poor. The difficulties of the introduction of congestion pricing will be discussed in Section 2.5.

2.2 Pricing Theory

The microeconomic theory of congestion pricing is well developed and straightforward once the cost of congestion and benefit of transportation are given. However, measuring the cost is not easy as it involves various internal and external cost elements[1]. Two main cost elements this thesis deals with are congestion cost (the cost of time loss) and air pollution cost. They are both external costs to road users and not reflected on their trip decisions unless some measures are taken to internalize them.

Taxation is one of the measures that are taken to internalize external costs. In the case of congestion cost, however, as the cost varies considerably depending on the facility or the time of day, taxes that are charged uniformly regardless of the driving pattern of users do not help internalize the cost. Therefore, the concept of congestion pricing that charges higher tolls when the level of congestion is high is more appropriate to internalize the congestion cost.

Cost of air pollution is also related to the level of congestion as the slow and sometimes "stop-and-go" traffic causes higher emissions than smooth flows. Therefore, the concept of congestion pricing is also applicable, and this will be further discussed in Chapter 4.

In this section, cost functions for congestion costs will be introduced as functions of traffic volume, which indicates the level of congestion. Then, the optimal toll for internalizing the congestion cost will be derived following the concept of marginal cost pricing.

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[1] The cost elements of road transportation will be discussed in Chapter 3.

2.2.1 Mechanism of Congestion

In this thesis, flow congestion on a major highway without traffic signals is analyzed for the sake of simplicity. When many vehicles enter the highway simultaneously, the resulting high *density* D (number of vehicles per unit distance) reduces average vehicle *speed* S. The *volume* or *flow* V (number of vehicles passing a given point per unit time) may either rise or fall as density increases. These three variables have the following relationship:

$$V = DS \tag{2.1}$$

Given Equation 2.1, the relationships among the three variables D, S, and V can be determined once the relationship between any two of the three is determined.

The relationship between V and D has the general shape shown in Figure 2-1-a. Using Equation 2.1, the relationships between S and D and between S and V can be expressed as shown in Figures 2-1-b and 2-1-c, respectively[2][49].

These relationships are instantaneous ones and defined over a very small region of time and space. In order to apply them to an economic analysis of a highway or a network, not only the number of vehicles passing through a certain point but also the number of vehicles attempting to enter at various points should be considered.

Several computer simulations have been run to analyze the effect of congestion on drivers' decision to enter a highway. Dewees (1978) simulated a ten-square-mile suburban road network in metropolitan Toronto and generated nine data points relating average travel time per mile to the entering traffic flow, holding flows on all other streets constant. Using these data, Small (1992) shows two widely used speed-flow functions (Figure 2-2)[49]. The first is a simple power function (solid line in Figure 2-2):

$$\frac{1}{S} = T_0 + T_1 \left(\frac{V}{C_p}\right)^k \tag{2.2}$$

where T_0, T_1, and k are parameters, and C_p is practical capacity defined as, "the maximum number of vehicles that can pass a given point on a roadway or in a designated lane during one hour without the traffic density being so great as to cause unreasonable delay, hazard, or restriction to the driver's freedom to manoeuvre under prevailing roadway and traffic conditions"[56]. This measure of capacity is equivalent to the "maximum volume at service level E[3]" of the Highway Capacity Manual[56].

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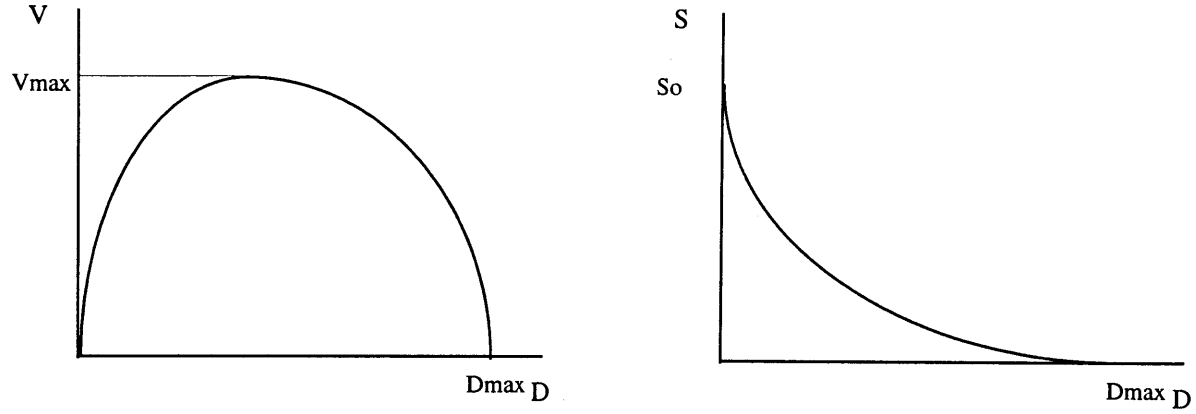
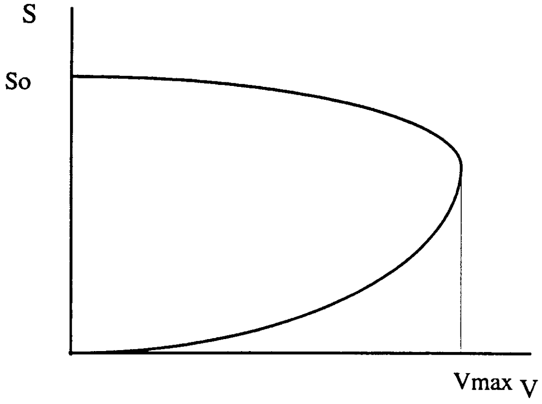
[2] Vehicles of different sizes or acceleration capabilities are converted to equivalent numbers of passenger cars in these relationships.

[3] The Highway Capacity Manual of 1992 defines the level of service (LOS) through A to F depending on the density of a road. LOS E is defined as a density greater than 32 passenger cars/mile/lane within the stable-flow range(up to the maximum flow)[56].



a. Volume-Density

b. Speed-Density



c. Speed-Volume

Figure 2-1: Representative speed-volume-density curves

The Bureau of Public Roads suggests values of 0.15 and 4 for T_1/T_0 and k, respectively [11]. Dowling and Skabardonis (1992) propose $T_1/T_0 = 1$ and $k = 4, 10$ and show they provide good fits to the Highway Capacity Manual curve[13]. The estimates for the data points in Figure 2-2 were 0.10 and 4.08 for T_1/T_0 and k.

Steenbrink (1974) used a steady state capacity C_s instead of C_p and suggested the values of 2.62 and 5 for T_1/T_0 and k[51]. The steady state capacity is defined as "the maximum steady-state flow on a link, i.e. the capacity of the point providing poorest service on that link" [4].

The second function is a piecewise-linear one (dotted line in Figure 2-2):

$$\frac{1}{S} = \begin{cases} T_0 & \text{if } V \leq V_k \\ T_0 + T_1\left(\frac{V}{V_k} - 1\right) & \text{if } V > V_k \end{cases} \tag{2.3}$$

This function is derived by Small (1983) to express the average travel time over a peak period of fixed duration[48]. V_k is a capacity parameter related to highway investment and not necessarily equal to C_p or C_s.

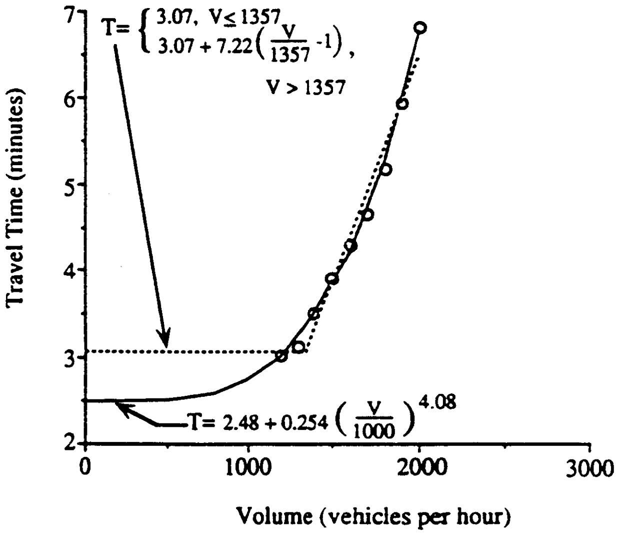


Figure 2-2: Simulated travel time–flow relationship, Don Mills Road S., Toronto

Source: Small (1992)[49]

Unlike the instantaneous relationships shown in Figure 2-1, these two functions capture some of the dynamic interaction crucial to highway congestion. Since they quantify the volume of traffic attempting to use the highway (demand), they can be used to analyze situations where demand exceeds capacity, which do not appear in the instantaneous relationship in Figures 2-1-a and 2-1-b[4]. In the analysis of road pricing, not the instantaneous relationships but the relationship between the demand and supply is required.

2.2.2 Congestion Cost

The relationship between travel time and flow-capacity ratio V/C (V/C_p, V/C_s, or V/V_k) described in the previous section can be extended to relate the flow-capacity ratio to the cost of travel time. This generalized[5] cost of travel time c can be divided into the cost on an uncongested road c_0 and the additional cost caused by congestion c_g (congestion cost).

$$c(V,C) = c_0 + c_g(V,C) = c_0 + f(V/C) \tag{2.4}$$

Using the two travel time functions described in Section 2.2.1, the congestion cost c_g can also be expressed in the following two forms.

Power function:

$$c_g(V,C) = c_2 \left(\frac{V}{C}\right)^k \tag{2.5}$$

Piecewise linear function:

$$c_g(V,V_k) = \begin{cases} 0 & \text{if } V \leq V_k \\ c_2\left(\frac{V}{V_k} - 1\right) & \text{if } V > V_k \end{cases} \tag{2.6}$$

These cost functions are shown in Figure 2-3 with the solid lines. These functions denote average cost per user in the sense that they are shared by all the users in volume V. The marginal cost (MC), defined as the additional cost of adding another user to volume V, can be derived as follows:

$$MC = \frac{d(V \cdot AC)}{dV} = AC + V \cdot \frac{d(AC)}{dV} \tag{2.7}$$

where AC is the average cost. Using Equation 2.7, two forms of the average cost functions (Equations 2.5 and 2.6) can be transformed into marginal cost functions.

Power function:

$$MC_g(V,C) = c_2(k+1)\left(\frac{V}{C}\right)^k \tag{2.8}$$

---

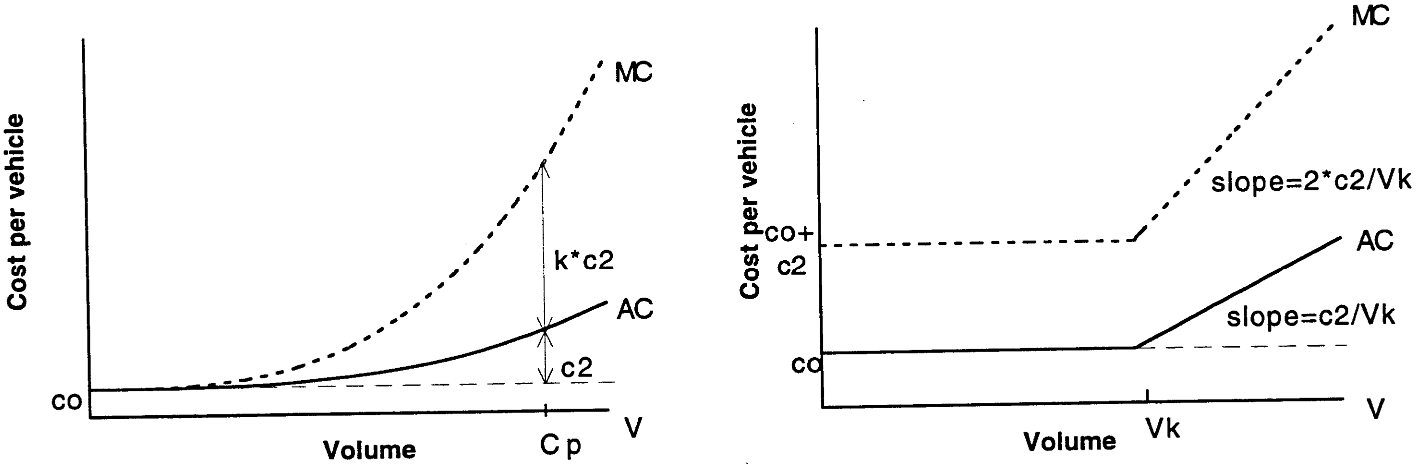
[4] The flow (V) does not exceed its capacity (V_m) in these figures, while the demand could exceed the capacity determined by the service level.

[5] The term "generalized" is used because this cost is not what road users pay directly but only what can be measured through the subjective value of time.

Piecewise linear function:

$$MC_g(V,V_k) = \begin{cases} 0 & \text{if } V \le V_k \\ c_2\left[2\left(\frac{V}{V_k}\right)-1\right] & \text{if } V > V_k \end{cases} \tag{2.9}$$

The marginal cost curves are shown in Figure 2-3 with the dotted lines.



a. Power function

b. Piecewise linear function

Figure 2-3: Cost functions of congestion

Source: Small (1992)[49]

2.2.3 Marginal Cost Pricing

A driver's decision before taking a trip is not based on the marginal cost of his own trip but on the average cost over all the users including himself. Suppose there is a highway already congested with volume V and a driver is thinking of entering the highway. The marginal cost of his trip, the aggregate additional cost associated with his entry, would be higher than the average cost that the drivers of volume V perceive. It was derived mathematically in Equation 2.7 and illustrated in Figure 2-3. However, the driver does not consider the marginal cost of his trip when he makes his trip decision, but instead his trip decision is based on the average cost. After all, every driver makes his trip decision based not on the marginal cost but on the average cost of his trip.

In microeconomic theory, maximum efficiency is achieved when the marginal cost is equal to the marginal benefit, or the demand. Producers do not have an incentive to increase production because an additional unit of production would bring more cost than revenue. However, since the marginal cost is not usually perceived by users in road transportation, the equilibrium in the transportation market lies beyond the efficient level of quantity and is obtained where the *average* cost equals the demand. Assuming a typical shape of the demand function, the graphical representation of the equilibrium point is given as (V_0, AC_0) in Figure 2-4. The maximum level of economic efficiency is achieved at the volume V_1, where the marginal cost curve intersects with the demand curve. This optimal level can be achieved if the difference between the marginal cost and the average cost is charged to users. The optimal toll τ for the two function forms is given in the following forms.

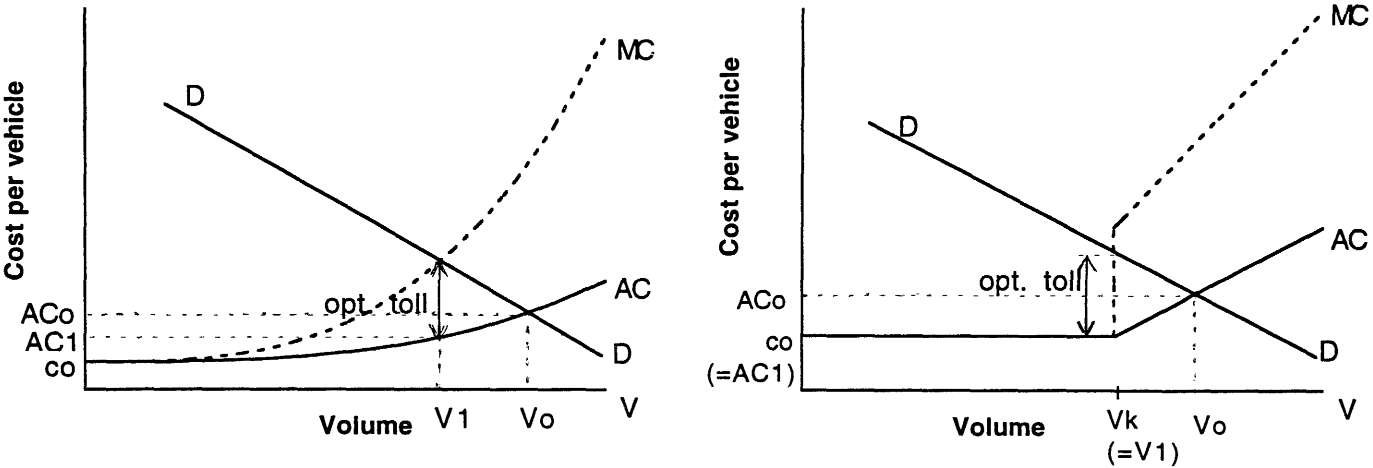
Power function:

$$\tau = c_2 k \left(\frac{V}{C}\right)^k \tag{2.10}$$

Piecewise linear function:

$$\tau = \begin{cases} 0 & \text{if } V < V_k \\ \text{undefined} & \text{if } V = V_k \\ c_2\left[2\left(\frac{V}{V_k}\right) - 1\right] & \text{if } V > V_k \end{cases} \tag{2.11}$$

For the piecewise linear function, the toll becomes undefined in terms of V if $V = V_k$. As illustrated in Figure 2-4-b, the optimal congestion fee is the fee that holds the demand just at the capacity.



a. Power function

b. Piecewise linear function

Figure 2-4: Optimal tolls

Source: Small (1992)[49]

2.3 Pricing Options

In practice, several technical and operational options are available for ways to collect tolls from users. In this section, various options both in technologies of toll collection systems and operational designs will be reviewed.

2.3.1 Technical Options

The key technology for congestion pricing is electronic toll collection (ETC). ETC is based on automatic vehicle identification (AVI), a functional area of Intelligent Transportation Systems (ITS). ETC allows the payment of tolls without making vehicles stop by identifying in-vehicle transponders with roadside detectors. This is a great advantage especially to a congestion pricing project aiming at environmental improvements since the vehicles would not emit additional pollutants or use additional energy at toll booths by stopping and accelerating. ETC is already used on some toll roads in the United States and abroad[6] and has already been proved to be highly reliable. According to Pietrzyk (1994)[46], "Existing technology has been known to operate in the 93 to 98% reliability range while most vendors claim that the reliability of new technology to be introduced is in the range of 99.95 to 99.99%".

Basic Structure of ETC

An ETC system consists of vehicles with in-vehicle transponders (identification tags), a two-way microwave link, a roadside reader, and a central computer system (Figure 2-5).

The in-vehicle transponders (identification tags or IC cards) store the information needed for toll transactions, such as vehicle type, account ID, balance, etc. The road side reader transmits and receives information from the transponders, identifies the vehicle, and conducts the transaction. The central computer system is used to access account information and process the transaction requests.

Technical Systems and Accounting/Debiting Methods

Depending on the capabilities of in-vehicle transponders, ETC systems can be grouped into several categories. Generally, the less transponders are capable of processing data, the less each user has to pay to participate, but at the same time, the central system is required to shoulder more complex tasks.

The simplest type of transponder is called read-only, or one-way. The transponder only receives information from the roadside detector. Therefore, all the transactions are made at the central computer, which is operated by a central authority. Users have their accounts in the central operating authority and tolls are debited from them. The central agency is able to keep track of virtually every transaction made by users. An issue of privacy is often raised due to this characteristic of the simplest

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[6] See Table 3 of Pietrzyk (1994)[46] (p.p. 489-497) for both planned and operating ETC projects.

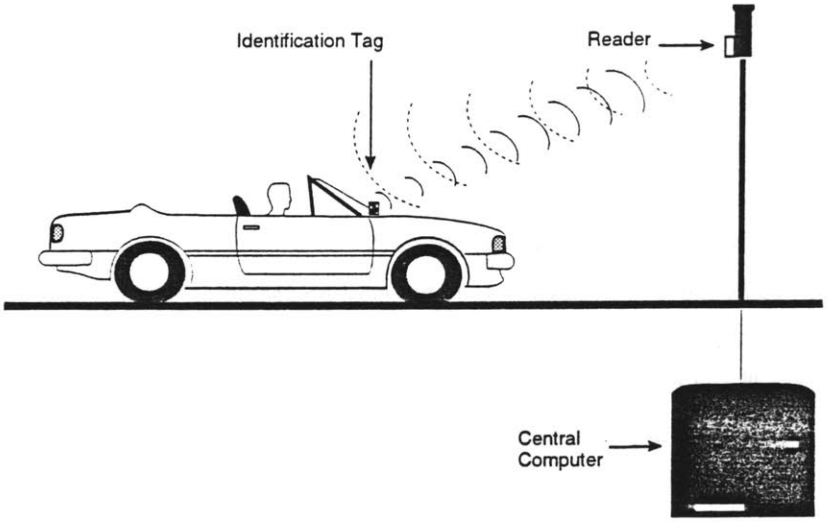

Figure 2-5: Electronic toll collection (ETC)

Source: TRB (1994)[57]

ETC system. However, this read-only system is known to have the highest technical reliability and require the lowest installation cost on the users. Thus, the implementation is relatively easy.

The more complex type of transponders are capable of recording some information sent from roadside detectors. These are called read/write systems. The simplest type of read/write transponders can only receive the transaction logs so that users can keep track of transactions every time they are made. This has the same problem of privacy as the simplest read-only transponders do since the transactions are still made at the central computer.

In order to avoid the privacy issue completely, transactions should be made on the vehicles. Therefore, transponders must have transaction capabilities. The smart card metering system, which undertake transactions directly on user-held cards, fits in this category. In this system, users can buy cards anonymously at shops or government offices, and fees are debited from those pre-paid cards every time their vehicles pass toll collection points. It is also possible to extend the use of cards to public transit fares.

Applications to Complex Pricing Schemes

The technological developments in ETC systems provide opportunities for applications of more complex pricing schemes like the "pollution-adjusted-rate" congestion pricing, which will be described in Chapter 4. As this pricing scheme requires vehicles to be charged with different amounts of tolls depending on their emission characteristics and time of day, manual collections are quite difficult in practice. However, if each vehicle is mounted with a tag to which information on the vehicle's emission characteristics is input, variable charges can be collected from the vehicles automatically.

2.3.2 Operational Design Options

Operation of congestion pricing could take several forms depending on the geographic area covered and types of facility included. In practice, congestion pricing is categorized in six basic forms[57]:

- Point pricing

  Users passing a point at a specific time are charged fees for passing that point regardless of the distance traveled on a specific route.

- Cordon pricing

  Users wishing to enter a congested area are charged fees at each entry point into the area.

- Zone pricing

  Users traveling within a cordoned area also pay fees.

- Higher charges for parking in congested areas

  This puts particular emphasis on parkers traveling during the most congested period.

- Charges for distance traveled

  Users traveling within a congested area or on a congested route are charged based on the distances they travel.

- Congestion-specific charges

  Users would be charged for both time spent and distance traveled.

The choice of these options should depend on goals of congestion mitigation level and the characteristics of current congestion problems, transportation systems and users, and institutional framework. They also require different costs and efforts for implementation and operation, and generated revenues also vary.

2.4 Experience and Current Movements

2.4.1 The Case of Singapore

Singapore has implemented unique transportation policies since the successful introduction of the Area Licensing Scheme (ALS) in 1975. The ALS is virtually the only working congestion pricing scheme of this scale in the world and is often cited as an effective means of transportation demand management. With the recent advances in smart card and communication technologies, the government has decided to fully automate the system. This is going to be a leading application of an Electronic Toll Collection (ETC) system; it is planned to be implemented by 1997.

The Singapore government has been attempting to solve the congestion problem by using demand management policies heavily depending on fiscal and monetary disincentives. Along with the ALS, the Certificate of Entitlement (COE) system, which mandates a person to purchase a certificate before buying a car, has proven to be effective to discourage the auto ownership.

The Area Licensing Scheme (ALS)

The ALS was introduced in June 1975 to discourage the widespread use of private cars for commuting purposes by imposing restrictions between 7:30 a.m. and 9:30 a.m. on entering a cordoned area of the Central Business District, called the "restricted zone" (See Figure 2-6). The system was operated by manual supervision at various entry points into the restricted zone. A city shuttle bus service was inaugurated with 15 fringe car parks built to encourage park-and-ride for those traveling into the restricted zone. Parking fees inside the restriction zone were raised in May 1975. Soon after the introduction of the ALS, the total number of motor vehicles entering the restricted zone had dropped significantly, but there was still a heavy concentration of traffic after the restriction times[34].

The pricing control was only applied during the morning peak hours and to private cars and taxis in the original scheme. This objective was revised in June 1989 to the use of ALS as a traffic management tool to curtail congestion. The new scheme was to charge vehicles for the use of road space at times and in places when and where they cause congestion. Hence, the restriction was extended to the evening peak hours and to include goods vehicle, non-scheduled bus, and motorcycle.

From January 1994, the ALS was further extended. The area covered was increased, and the restrictions became effective all day. The four-passenger rule for cars exempted from the ALS fee was abandoned because drivers were ingeniously *borrowing* passengers to pass the gantry points. Table 2.1 shows how the system has changed over the past two decades of operation.

Effects on Transportation Systems

The most significant effect of the ALS is the reduction of traffic both into and out of the restricted zone during the restricted hours. When the original ALS was implemented in 1975, the inbound traffic entering the restricted zone during the restricted hours dropped 44% from about 74,000 to 41,500 vehicles (all classes). Since goods vehicles were not restricted under the original ALS, the number of those vehicles entering the restricted zone increased, and the inbound traffic climbed back

	Original ALS(1975-)	Revised ALS (1989-)	Revised ALS (1994-)
Objective	Manage the widespread use of private cars	Congestion Pricing	Congestion Pricing
Restricted Zone (Area)	610 ha in 1975; increased to 710 ha after 1986	725 ha	(More than 725 ha)
Restricted Hours	7:30-10:15 a.m.	7:30-10:15 a.m. 4:30-6:30 p.m.	All day
Restricted Vehicles	Private car, company car, and taxi	Private car, company car, taxi, goods vehicle, non-scheduled bus, and motorcycle	All vehicle (private and public)
Daily ALS Fees	S$2 for taxi; S$5 for private car; and S$10 for company car (cars owned by companies for business purpose)	S$3 for car, taxi, goods vehicle, and non-scheduled bus; S$1 for motorcycle; and S$6 for company car	S$3 from 7:30 a.m. to 6:30 p.m. S$2 from 10:15 a.m. to 4:30 p.m.

Table 2.1: Changes of ALS

Sources: Menon, Lam, and Fan (1993) and Low (1995) [39, 34]

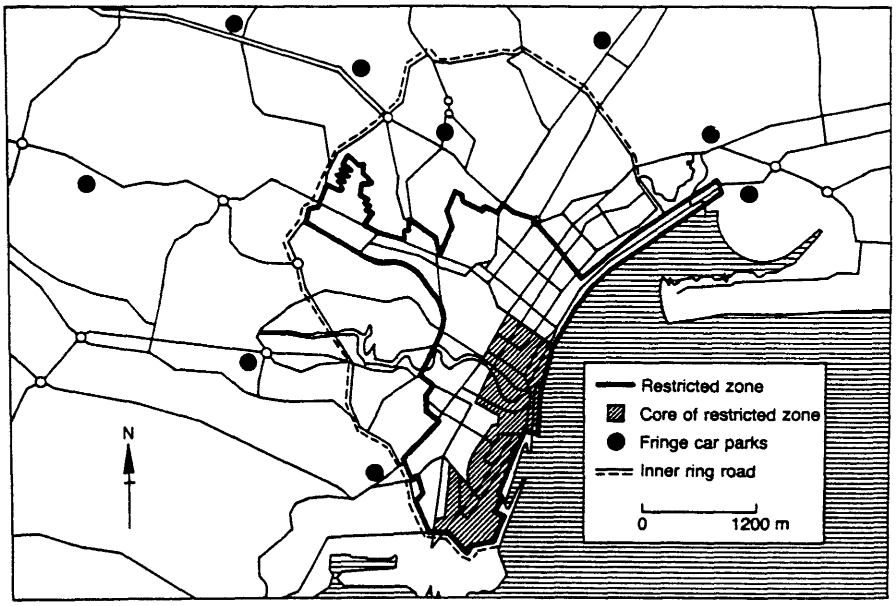

Figure 2-6: Restricted zone for the Singapore's ALS

Source: Lewis (1993)[33]

to nearly 60,000 vehicles in 1985. However, the total inbound traffic during the restricted hours had been capped at below 70% of the pre-ALS level although employment in the restricted zone had grown by 30% between 1975 and 1989.

The revision in 1989 to include all vehicles except for scheduled buses and emergency vehicles reduced the number of goods vehicles and motorcycles during the restricted hours. The extension of restricted hours to include evening peak hours resulted in about 45% reduction in inbound traffic for all vehicles and about 30% reduction in outbound traffic during the period. Although the ALS effectively reduced the volume of traffic during the restricted hours, the traffic volumes in between those peak periods were high and had sharp peaks right before and after the restricted hours (Figure 2-7).

The ALS had created a high volume of traffic during the day time as some drivers avoided the restricted hours. Similarly, the traffic volumes outside the restricted zone during the restricted hours had increased as more vehicles avoided the restricted zone. The average speed along the ring road outside the restricted zone was 19 km/h as compared to 31 km/h in the restricted zone during the evening restricted hours in 1989. One of the criticisms of the ALS is that it has not really improved traffic conditions but merely pushed them somewhere else. However, an opposing argument for this criticism could be the strong impacts of the ALS on the mobility within the restricted zone and the

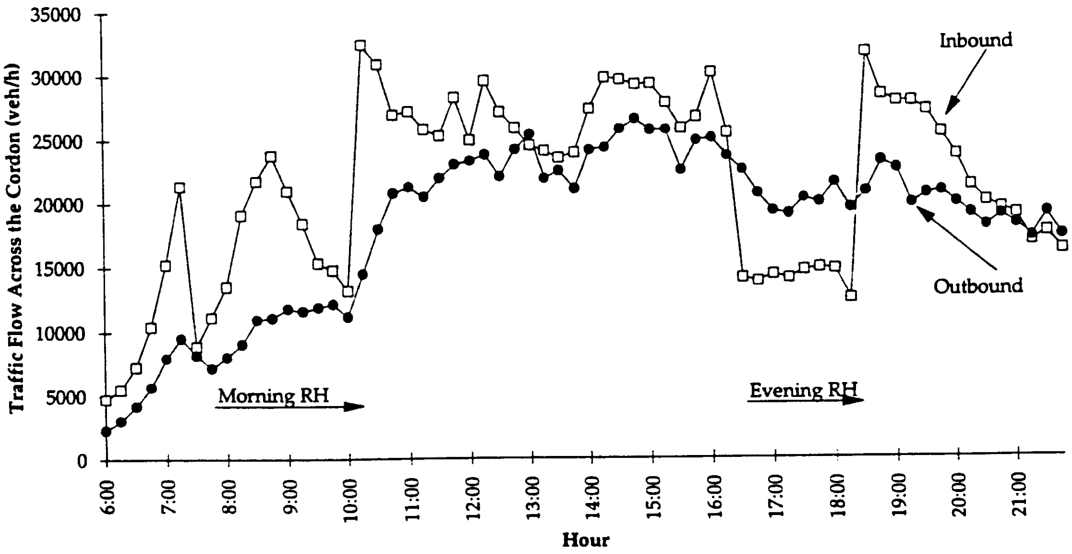

Figure 2-7: Variations in hourly traffic volumes entering and leaving the restricted zone (February 1990)

Source: Menon, Lam, and Fan (1993)[39]

positive effects on the modal split. Within the restricted zone, the reduced traffic resulted in an increase in travel speeds during the restricted hours.

The implementation of the revised ALS in 1989 had brought an increase in travel speed during the evening restricted hours from 25 km/h to 32 km/h in average.

The modal split for the three major transportation modes to the restricted zone was affected by the ALS, resulting in a shift of private car users to public transit. As shown in Figure 2-8, the transit share of work trips to restricted zone increased from 33% in pre-ALS years to 69% in 1983. The large increase in the bus mode must have been a result of the restriction on private car use as some people were forced to change to a public transit. Also, the improved bus service resulting from the increased travel speed in the restricted zone must have contributed. The opening of Mass Rapid Transit (MRT) in 1988 attracted about 11% of users, but the modal split between public transit and private cars did not change considerably from 1983 to 1988.

Costs and Revenues

The capital cost of the original ALS totaled S$6.6 million in 1975. In addition, there was a monthly operating cost that averaged about S$59,000 in the first years. For the revised ALS, the capital costs amounted to only S$170,000, mainly for the installation of overhead gantries at a few additional

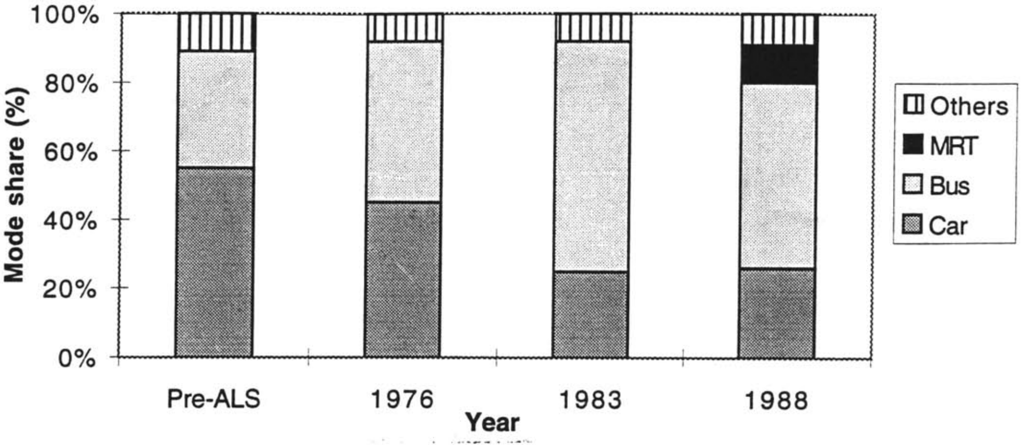

Figure 2-8: Variations in modal split of work trips to the restricted zone

Source: Menon, Lam, and Fan (1993)[39]

entry points to cover an expanded restricted zone. However, the increased manpower requirements for both the morning and evening restricted hours pushed the average monthly operating costs to about S$295,000, more than five times of the original ALS. The revenue from the ALS is mainly in the sale of licenses and the collection of fines. In Singapore, revenues related to motor vehicles and collected by the Registry of Vehicles and the Customs and Excise Department[7] account for S$2.9 billion, about one-fifth of the total tax revenue in 1993. The ALS has been bringing a large portion of the government's revenue with low, capital and operating costs.

2.4.2 The Case of Hong Kong

With the real GDP growth rate averaging about 7.6% from 1975 to 1994, Hong Kong has gone through a rapid motorization. The number of registered vehicles grew at a rate of 5.2% a year in the same 20-year period, while the population grew only by 1.6% per year. Despite the government's high investment in transportation construction projects, public roads have only increased by 2.2% annually. This rapid motorization has caused rising problems including congestion, and the government has implemented several demand management measures. The first registration tax (FRT) and annual vehicle license fees (ALFs) have helped reduce auto ownership and are still in effect. However, electronic road pricing (ERP), or a congestion pricing program tested in 1985, was not

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[7] Motor vehicle related tax includes motor vehicle taxes (additional registration fees, road tax, special tax on diesel engines, passenger vehicle seating fees, non-motor vehicle licenses), motor vehicle import duty, and gasoline tax[34].

implemented due to political difficulties.

Demand Management in Hong Kong

Reacting to the rapid motorization, the government of Hong Kong launched the first Green Paper on internal transportation policy in 1974. The Green Paper set out to implement a tripartite transportation policy: to improve the road system, to expand and improve public transportation, and to use road space more economically. One effective way proposed to enhance efficient use of road space was a fiscal measure to restrain auto ownership. The first registration tax (FRT), or a purchase tax, was raised by 50% to 15% of the cost, insurance, and freight (CIF) value on all private cars and motorcycles. Annual vehicle license fees (ALFs) were almost tripled, with the highest levels targeted mainly at private cars[27]. Although the FRT and the ALFs led to a decline in the number of private vehicles, the number of goods vehicles increased instead since goods vehicles were exempted from those charges.

The total number of vehicles started to rise again in 1976 and kept rising until the FRT and the ALFs were increased drastically in 1982. The FRT was doubled to 70%–90% of a vehicle's value (CIF), and ALFs were tripled. The number of private cars declined yearly from 1982 to 1986, but it grew beyond the 1982 peak in 1990. Similarly, the number of motorcycles registrations also declined for six years from 1981, but it exceeded the 1981 peak in 1994.

Electronic Road Pricing (ERP)

The government of Hong Kong announced in 1983 that it would start the world's first technical feasibility study of electronic road pricing (ERP) through 1985. This pilot project was based on a system of automatic vehicle identification (AVI) technology with a passive electronic number (license) plate (ENP), the size of a video cassette, mounted underneath the vehicle. When a vehicle passes over a toll location, electronic loops embedded under the road surface detects the moving vehicle's ENP and relays the vehicle's identification code to the computers in the control center through roadside equipment (Figure 2-9). At the control center, a management and accounting system processes the data and bills road users automatically on a monthly basis. A closed-circuit television system was used to detect violators by photographing the license plates of their vehicles.

The system was test-run in the Central/Admiralty area for a period of 8–12 months: 2,600 vehicles were fitted with ENPs, and 18 toll locations were equipped. Of the 2,600 vehicles tested, a half were government-owned vehicles, a quarter were buses, and the rest were owned by volunteers. The control center handled approximately 30,000 transactions per day[59].

Three cordon schemes (Schemes A, B, and C) were tested on different areas with different charging

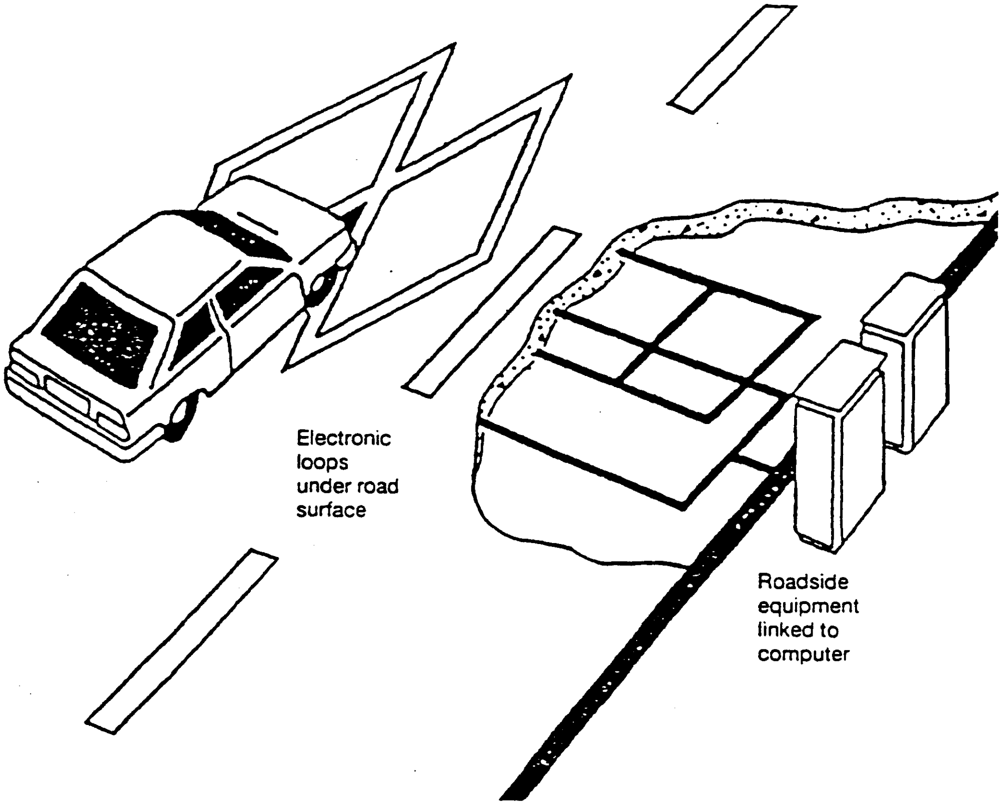

Figure 2-9: Schematic illustration of Hong Kong's electronic road pricing (ERP) system

Source: OECD (1988)[45]

characteristics (Figure 2-10 and Tables 2.2 and 2.3).

Scheme	Area		Other characteristics
	zones	toll locations	
A	5	130	
B	5	115	Additional directional surcharge of HK$1
C	13	185	Commercial vehicles were excluded

Table 2.2: Characteristics of cordon schemes

Source: Lewis (1993)[33]

Category	Shoulder	Peak	Inter-peak	Off-peak	Tidal surcharge
Hours	7:30–8:00	8:00–9:30 17:00–19:00	9:30–17:00	19:00–7:30 Saturday and Sunday (all day)	Applied for peak and inter-peak periods
Tolls	HK$1, HK$2, or HK$3	HK$2, HK$4, or HK$6	HK$1, HK$2, or HK$3	No charge	HK$1

Table 2.3: Hours and the amount of tolls

Source: Lewis (1993)[33]

The pilot project was a technical success "with 99.7% of reliability" [27]. Accompanying evaluation projected that the gross revenue would be HK$395 million in Scheme A, HK$465 million in Scheme B, and HK$540 million in Scheme C (all in 1985 Hong Kong dollars)[27]. It is also forecasted that peak period traffic would be reduced by 20% and congestion would be reduced significantly [20]. Overall impacts were estimated to be very positive. The revenue was estimated to be far more than the annualized capital and operating costs of HK$49 million (Scheme B) to HK$52 million (Scheme C).

Despite the greatly successful pilot project, the government could not move on to the full implementation for several reasons. One factor was suspicion that it was just a government revenue-raising scheme. Another factor was privacy. Since the use of vehicle-mounted transponders enabled authorities to track citizens, the public reacted sensitively given the 1984 Sino-British Joint Declaration on the future of Hong Kong. Some evaluators believed that the government made a tactical error in developing the program during a time of decline in stocks and property values and after major public transit improvements had already eased congestion.

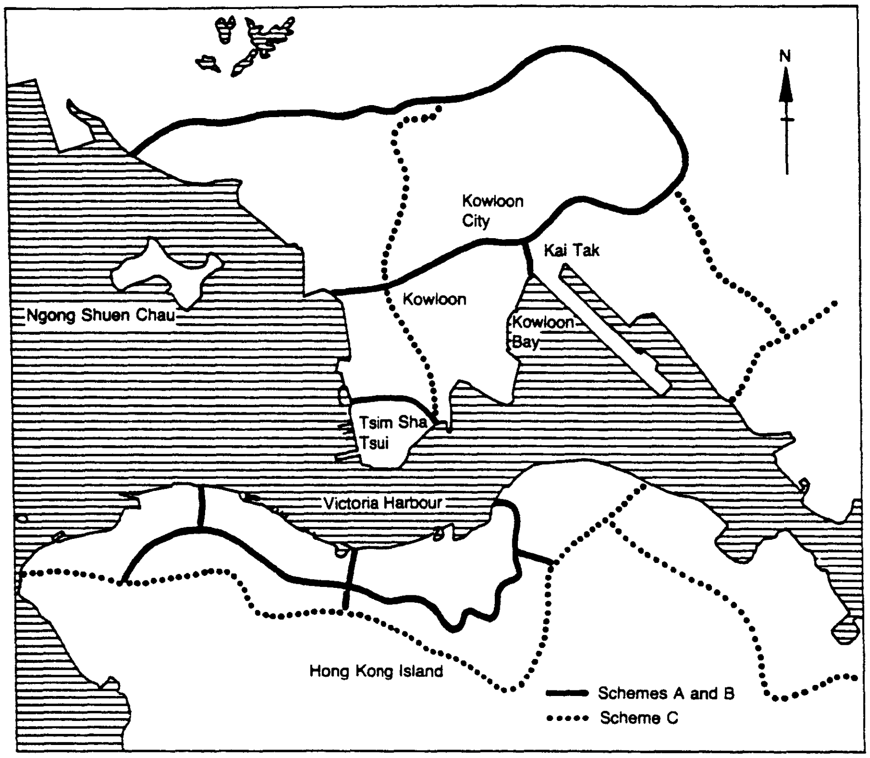

Figure 2-10: The cordon schemes tested in Hong Kong

Source: Lewis (1993)[33]

2.4.3 The Case of Japan

Although Japan has not adopted congestion pricing schemes, several analyses were conducted during the 1970's for large cities including Tokyo, Osaka, and Sapporo[60]. Currently, congestion pricing has been emphasized in the "New Traffic-Congestion Mitigation Action Program," which was published by the national government in 1993 as a part of the 11th Five-Year Road Improvement Program. Congestion pricing may be accepted relatively easily in Japan since an extensive toll road system has been used since 1952, and people are used to paying for much higher amounts of tolls than the United States.

The Toll Road System

The toll road system was first adopted on a full scale in 1952. This system functions by borrowing the necessary funds for planned construction from the special account of the fund application department, and then repaying the loan with toll fees levied from the users of the completed road. As of January 1993, approximately 4,900 mi (7,900 km) of toll roads were operating (Figure 2-11), and these roads, including urban expressways, inter-city highways, and bridges between islands, are operated by several public bodies such as Japan Highway Public Corporation, designated city expressway public corporations (including Metropolitan and Hanshin Expressway), Honshu-Shikoku Bridge Authority, local road public corporation, and local public bodies[28].

The levels of tolls are set based on the following principles:

- Redemption principle

  The total cost of construction, maintenance and management, interest payments, and other expenses should be recovered over the collection period (redemption period).

- Fairness and validity principle

Tolls are substantially higher than American tolls, and they are divided into several vehicle groups depending on their sizes. ETC systems are not introduced widely, but a pre-paid card called "highway card", which is debited manually at toll booths and gives some discount compared to a cash payment, has become quite popular.

New Traffic-Congestion Mitigation Action Program

The New Traffic-Congestion Mitigation Action Program, a five-year emergency action plan, was drawn up in 1993 as a part of the 11th Five-Year Road Improvement Program. It emphasizes the

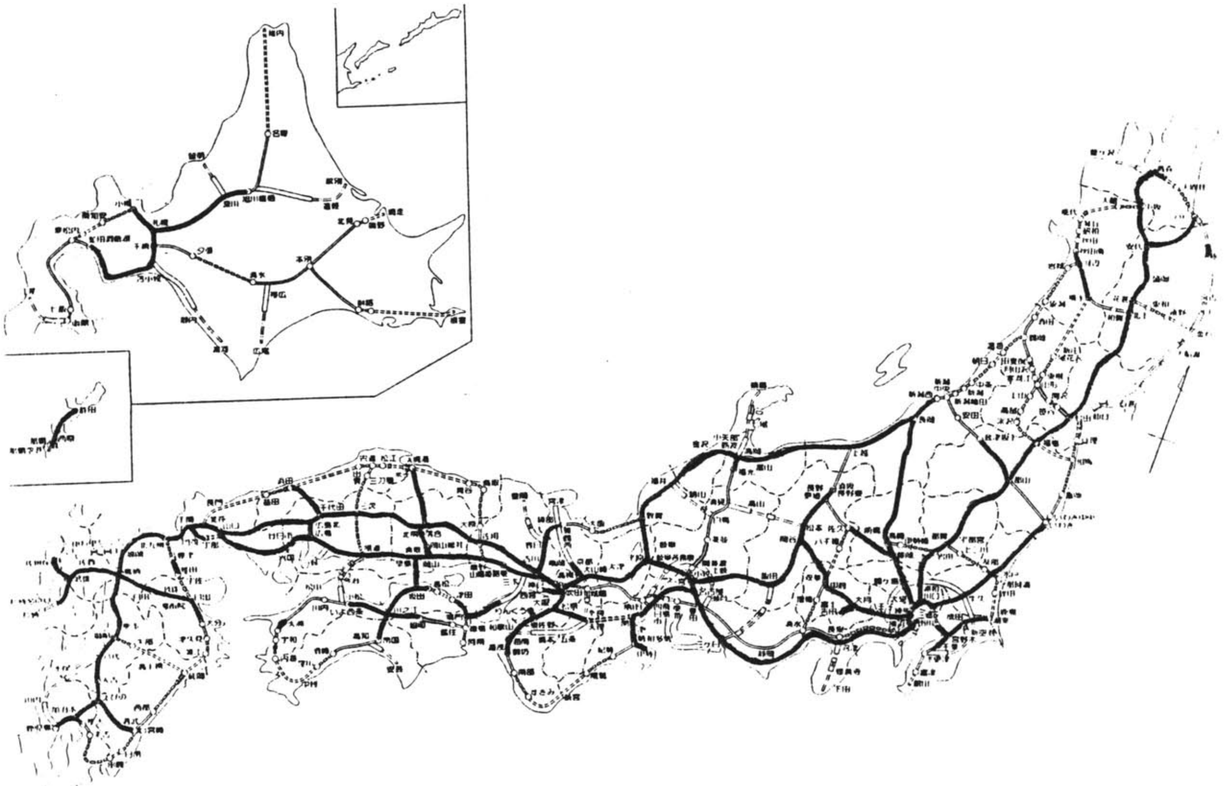

Figure 2-11: Toll roads in Japan

Source: Ministry of Construction (1994)[41] importance of transportation demand management (TDM) and suggests the possibility of congestion pricing.

2.4.4 The Case of Europe

France

In 1992, the toll road authority that operates autoroutes in France introduced peak period pricing on Autoroute du Nord A1, which connects Paris with Lille. The heaviest congestion on this route was found on weekend afternoons[8], when Parisians return from weekend trips. Users are charged based on the distance traveled. The peak prices were set at 25 to 50% higher than base rates, and off-peak period rates were reduced by 25 to 50% of base rates[53].

The pricing dramatically reduced congestion during the most congested periods. Although the new peak now occurs just before the high-priced times, it is at least 10% below the original peak traffic levels [20].

Norway

Norway has implemented various large-scale road pricing schemes demonstrating the technological feasibility of AVI and public acceptance of road user charges as a means for financing roads and transit.

In Oslo, the capital of Norway, 18 toll points[9] were set up around the city center in February 1990. The cordon system, often called "toll ring", has helped raising additional revenues for the development of the main road system. The AVI technology was introduced in December 1990, and a multi-trip prepayment system introduced in October 1991 proved to be popular among users [33]. Currently, the fee is a flat rate at all times, but planners are considering switching to congestion pricing that would set up peak/off-peak differentials.

A historic city of Bergen employs a central area pricing program using six toll collecting points. The toll system operates from Monday to Friday between 6:00 a.m. and 10:00 p.m. for all traffic entering the city. There is no charge on leaving the city and for public service vehicles. The fee is a flat rate at any time during the operation and paid in cash or by ticket at the manually operated toll booths. Currently, over half of Bergen's residents are in favor of the system. The simplicity and equality of the system enhances its acceptability to the public.

Another historic city, Trondheim, located on the coast of middle Norway, uses AVI to charge

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[8] Sundays from 4 to 8 p.m. were the worst.

[9] Currently, there are 19 stations.

all vehicles entering the city except for public service vehicles between 6:00 a.m. and 5:00 p.m. on Monday through Friday. Differential time charges are applied for 6:00 a.m. through 10:00 a.m. and 10:00 a.m. through 5:00 p.m. Currently, there are 24 different fees depending on vehicle categories and time periods [33].

The United Kingdom

The introduction of road pricing has been considered in the UK for a long time. In 1963, a Ministry of Transport's report concluded that, "with the deficiencies of the existing methods of taxation, the introduction of direct user charges would be required to address the economic effects of traffic congestion"[42].

A congestion pricing study for London under the auspices of the national government began in 1991 . The study examined a wide range of charges and evaluated potential impacts on travel, business, and property market values. It identified the major concerns of the public and suggested a need for collateral actions that would make the congestion pricing program acceptable to the public[20].

Cambridge is planning an areawide pricing strategy. The plan is to charge entry and movement within an area whenever congestion exists. Smart cards will be debited when vehicle movement is slow. Revenues are earmarked for public transit[20].

2.4.5 The Case of the United States

During the 1970's the Urban Mass Transportation Administration (UMTA: now Federal Transit Administration) started a demonstration program to implement congestion pricing on surface street systems in downtown areas. Despite the favorable estimates of the preliminary studies, none of the localities actually implemented the scheme. Among the main concerns were the possible adverse impacts on the local business and the poor. In the late 1970's, the UMTA changed direction to testing parking charges.

New York studied the potential of implementing congestion pricing for downtown streets in Manhattan in 1986, but the program was not implemented, again due to concerns about possible adverse effects on business and low-income groups[20]. It has also been studying congestion pricing for bridges and tunnels leading into Manhattan and for the downtown street system.

In 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) established the Congestion Pricing Pilot Program to support the initiation and implementation of five operating congestion pricing projects. Congestion pricing pilot pre-project feasibility studies and implementation projects are currently underway in: San Diego, Orange County, and San Francisco, CA; Lee County, FL;

Houston, TX; Minneapolis-St. Paul, MN; Boulder, CO; New York, NY; and Portland, OR [19].

The UMTA Experience in 1970's

Between 1973 and 1978, the UMTA, the predecessor of the Federal Transit Administration (FTA), worked with numerous cities in the United States in an attempt to implement congestion pricing demonstrations in the central business district (CBD) core areas. The main focus was on the congested surface street systems in downtown areas. The proposal was to use supplementary licenses in the form of daily, weekly, and monthly windshield stickers to administer the congestion charges for the use of streets in the designated zone. The proposal also included the future use of the automatic vehicle identification (AVI) technology. The expansion of transit services was thought to be an integral part of the project.

Boston, MA; San Francisco and Berkley, CA; Honolulu, HI; and Madison, WI responded positively and conducted preliminary studies. The preliminary assessments showed that congestion pricing would significantly reduce traffic, promote the use of transit service, and generate new revenues for the localities. It was estimated that daily charges of \$2.00 to \$3.00 (dollars at the time) for entering the downtown areas would reduce vehicle trips by 15% to 30%, increase speeds by 50% or more within the priced zones, produce the annual revenue of tens of thousands of dollars, at a program cost of less than one-tenth of the revenues [20].

Despite all these favorable estimates, however, none of the sites agreed to go beyond the preliminary assessments and implement the demonstrations. It was mainly because of the strong concerns about possible adverse impact on business and low-income groups. Arrillaga (1993) gives some other factors which led to the unsuccessful implementation of the program[1]:

- The focus was on relatively small core areas where the program could not produce dramatic reductions in overall trip times for typical travelers.
- The major reason for the interest in the concept was the anticipation of future extreme congestion, not actual existing levels.
- There were serious concerns about the feasibility of administering and enforcing the programs in the U.S. context. (State statutes did not allow mail citation of vehicle owners for moving violations, making the use of photo-radar surveillance techniques difficult.)

In the late 1970's the UMTA changed the direction of the congestion pricing demonstration program to parking pricing programs as a means of managing traffic demand. Since then, some localities have implemented parking price increases or parking subsidy reductions aimed at commuters or other selected vehicles parking in certain core areas and activity centers.

The Congestion Pricing Pilot Program

The Congestion Pricing Pilot Program was authorized under Section 1012(b) of the ISTEA, with the objective of encouraging testing and evaluation of congestion pricing projects in a variety of settings nation wide, on an experimental, "pilot" basis. A maximum of $25 million was authorized annually for the fiscal years 1992 through 1997 for the program.

An extensive plan of research and technical study has been developed to support the program. It includes the following activities [19].

- National Research Council Report
  The National Research Council (Transportation Research Board) conducted an exhaustive review of issues, opportunities, and potential impacts of congestion pricing; and issued a 2-volume publication in 1994[57].

- Guidance on Air Quality Impacts and Emission Credits
  Under the management and oversight of the Federal Highway Administration (FHWA) and the Environmental Protection Agency (EPA), guidelines are being prepared for states and localities on technical analysis and modeling approaches to assessing the travel and emissions impacts of proposed market-based strategies including congestion pricing.

- Institutional and Political Issues in Congestion Pricing
  Under FHWA sponsorship, researchers at the University of Minnesota are conducting a study to identify the critical institutional and political barriers to the implementation of congestion pricing.

- Equity Impacts of Congestion Pricing
  Under FHWA sponsorship, a study is being conducted on the distributional effects of congestion pricing. Public outreach workshops were held in Harlem and Brooklyn, NY, and Washington, D.C. with members of low-income communities and the transportation disadvantaged to determine who might be adversely impacted by congestion pricing, the extent of these impacts, and to discuss how such impacts might be successfully mitigated.

- Variable Tolling Study
  This research effort is designed to investigate the potential for the use of variable pricing such as peak-period surcharges and off-peak discounts on existing toll facilities.

- Congestion Pricing Guidelines

  In May 1994, the Department of Transportation (DOT) published Congestion Pricing Guidelines [20] as a resource report for potential partners in the program and others interested in promoting congestion pricing at the local level.

In addition to these research activities, several pilot projects are under way [19]:

- San Diego HOV Lane Pricing

  The FHWA has approved of this three phase project to allow single occupancy vehicles (SOV's) to "buy-in" to an existing HOV facility on Interstate 15 in Northeast San Diego. The revenues generated from the congestion pricing project will help provide more public transit along I-15 corridor and better access onto the Express Lanes for those who rideshare.

- Orange County, California, SR 91 Express Lanes

  The first privately-funded express lanes were built under California law (Assembly Bill 680) for 10 miles (four lanes) along State Route (SR) 91. The project started its operation in 1995[10]. The express lanes use automated peak-period pricing techniques to maintain free-flow traffic conditions. Testing of automated vehicle identification (AVI) equipment is also underway.

- Lee County, Florida Pilot Project

  This project involves environmental reviews, examination of alternative pricing strategies, marketing surveys, and traffic and revenue studies. Pricing concepts will also be intended to extend to MidPoint Bridge, which is now under construction. The use of pricing concepts is intended to encourage reduction of congestion during normal peak travel times by offering incentives for off-peak travel by specific local population groups such as senior citizens and students.

- The San Francisco-Oakland Bay Bridge

  The Metropolitan Transportation Commission (MTC) approved a draft congestion pricing strategy in 1994 recommending a $3 charge Westbound in the morning and evening peak periods plus mobility alternatives[11]. Despite local support, approval by the State legislature has not been granted, and action on the pricing initiative will be deferred until 1996 or 1997.

- The Southern California Association of Governments

  The Southern California Association of Governments, in cooperation with the California Department of Transportation (Caltrans), is conducting a preproject feasibility study for conges-

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[10] New York Times, January 2, 1996.

[11] They include improvements in the parallel transit services and rideshare programs.

tion pricing applications in the region. The study includes analysis of vehicle miles of travel and emission fees.

- Houston, Texas

  The Texas Department of Transportation (DOT) is conducting a feasibility study of a HOV "buy-in" strategy along an existing expressway spanning 13 miles of Interstate 10 (I-10) in Harris County, TX.

- Minneapolis-St. Paul, Minnesota

  The Minnesota DOT, in cooperation with the Metropolitan Council, is conducting a preproject study of potential congestion pricing applications and efficiencies in the St. Paul-Minneapolis metropolitan area. The structure is innovative in the manner that it encourages private citizen involvement in establishing priorities for regional transportation plans and programs. This public outreach process is named as a 3-C (continuing, cooperative, and comprehensive) planning process[36].

- Boulder, Colorado

  The city of Boulder, in cooperation with the Colorado DOT, is conducting a study of the feasibility of implementing congestion pricing in the Boulder metropolitan region. The project will incorporate an extensive public involvement program.

- New York State Thruway Authority

  This preproject study will commence with a user survey to explore the potential benefits and impacts of a congestion pricing program on the Tappen Zee Bridge in New York.

- Portland, Oregon

  Portland Metro and the Oregon DOT are conducting a study designed to determine the technical and political feasibility of congestion pricing in the Portland region. A program of public involvement will be carried out.

Automated Vehicle Identification (AVI) Technology Applications

The AVI technologies[12] have been applied to an increasing number of toll roads and airports to charge users automatically.

The North Dallas Tollway records 25 million toll transactions annually; and the Oklahoma Turnpike Authority had equipped 90,000 vehicles with AVI as of 1991[20]. Texas DOT issued 1,000

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[12] See Section 2.3.1 for description on AVI technologies.

vehicle identification tags to commuters who use Interstate 10, Interstate 45, and U.S. Highway 290 in the Houston area, not to charge the users but to obtain traffic condition information through roadside readers installed at intervals of as close as one mile (1.6 km)[12]. The Ted Williams Tunnel in Massachusetts, which opened for commercial vehicles in December 1995, adopts an ETC system; and the other two cross-harbor tunnels and 135-mile Massachusetts Turnpike are expected to be installed with the system as well[13].

Los Angeles Airport (LAX) in California installed a state-of-the-art AVI system in 1990 to reduce traffic congestion and maximize revenues collected from their ground transportation operation. All 5,500 commercial vehicles, car rental and hotel courtesy shuttles, limousines and shuttle vans are counted and the appropriate fee assessed each time they make an appearance at the airport. Shuttle vans are allowed up to three loops for the basic access fee of $1, and an "excess circuit" fee of $10 is charged for each additional loop.

Since the implementation of the AVI system, revenue collection has increased more than 250% and congestion has been reduced by 20%, compared to the honor system previously used by the airport[32].

Other airports using an AVI monitoring system include San Francisco and Oakland in California, Seattle-Tacoma in Washington, Salt Lake City in Utah, Pittsburgh in Pennsylvania, John F. Kennedy in New York, Miami-Dade in Florida, Minneapolis in Minnesota, Dallas-Fort Worth in Texas, Albuquerque in New Mexico, and Denver International Airport in Colorado.

2.5 Implementation Difficulties

As the previous experiences and current projects indicate, the key to a successful congestion pricing system is often to gain the political acceptance of the system and the willingness of the public to pay the proposed charges.

2.5.1 General Acceptance

After an introduction of a road pricing system, people's reaction fall into the following three categories[64]:

- individuals who are "tolled" are forced to pay for a commodity which used to be free
- individuals who are "tolled-off" are forced into less desirable modes, routes, or times of travel

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[13] The Boston Globe, December 14, 1995.

- individuals who are "untolled" (e.g. alternative mode or alternative road travelers) are worse off due to more congested traffic.

In general, without any form of compensation from the earned revenues (collateral actions), road users with a low value of time are worse off. In the United States, people are accustomed to using roads without paying out-of-pocket fees at the time of use; obtaining public acceptance may not be easy. However, a national opinion poll found that two-thirds of motorists who experience congestion say they would pay to avoid delay. About 4 in 10 would pay at least \$2.00 per day and another 2 in 10 would pay at least \$0.50 [57].

2.5.2 Distribution of Benefits and Costs

While congestion pricing increases the overall efficiency, there will be winners and losers in general. An important consideration in assessing congestion pricing is equity—how benefits and costs of the pricing affect particular groups. In the case of tolling an existing road or bridge, the potential winners and losers would be [57, 2]:

Winners

- Users with high values of time
  Their value on the time saved is substantially higher than the cost of the toll, and they pay the toll to stay on the route.

- Travelers already using bus or high-occupancy-vehicle services
  Such travelers would benefit from time savings and the toll would be divided among several users.

- Most commercial users of the road system
  They would benefit from more efficient delivery systems.

- Recipients of the toll revenues
  Large new revenues generated from congestion pricing would benefit some population groups depending on the use.

- Population segments who will enjoy cleaner air
  As reduced congestion generally lowers emission levels, people living or working near high concentrations of road-related local air pollution would benefit from cleaner air.

Losers

- Users with low values of time who stay on the tolled route for lack of alternatives ("tolled")

- Users with low values of time who shift to an alternative, but less convenient route/mode ("tolled-off") and those who decide to forego the trip.
- Users of unpriced facilities in the region ("untolled")
- Certain businesses in the region that might lose competitive posture compared to those in outlying uncongested areas

As a congestion reduction policy, congestion pricing has a greater impact on equity than road capacity expansion because congestion pricing excludes users with low value of time while capacity expansion has more indifferent effects on all users. However, the fact that only the low-valued trips are excluded also indicates that the potential improvements in efficiency are high as the cost of exclusion is smaller than in the case where some trips are excluded indifferently. Vickrey (1994) illustrates this point using calculations for a bottleneck congestion problem (pp.323–332 of [61]).

In a political context, the issue of equity is sometimes more important than the overall efficiency. If a pricing program is seen to force low-income people out of the facility, political consensus for the program will be difficult to obtain.

Therefore, in order to achieve political consensus, the re-allocation of revenues from pricing must be carefully made so that the benefit can be distributed to various kinds of people including low-income people. Improvements in transportation facilities such as public transit can be coupled with a pricing program for this reason.

The "pollution-adjusted-rate congestion pricing", which will be introduced in Chapter 4, requires more careful consideration for this issue of equity. Under this pricing scheme, old vehicles, which are more likely to be owned by low-income people, are charged with higher tolls as their emission levels are higher.

2.5.3 Privacy

Road users could be expected to resist toll collection technologies if they invade their privacy. Privacy concerns were one of the major factors which led to the failure of the implementation of congestion pricing project in Hong Kong in 1980's. Even though it was partly because people were sensitive to privacy issues due to the political transition (Section 2.4.2), the issue of privacy could be a major concern in any case.

However, as mentioned in Section 2.3.1, new technologies such as the smart card system would reduce the privacy concerns considerably since those technologies allow anonymous transaction with pre-paid cards.

2.5.4 Summary

This chapter has described theoretical and practical aspects of congestion pricing. The economic theory of marginal cost pricing is simple once the uncertainties on the cost and drivers' behaviors are put aside. The optimal tolls were derived as a function of traffic volume, and they provide higher economic efficiency to the society in an aggregate level.

Although the economic benefit is promised in an aggregate level, it does not mean every individual can be better off. This issue of equity has been a major obstacle for practical implementations of congestion pricing as several past experiences indicate. In order to mitigate the negative impact on low-income people and obtain a political consensus, collateral actions using the revenues from pricing policies, such as improvements in public transit and rideshare program, have been considered.

Another major obstacle for practical implementations has been an issue of privacy on ETC systems. Recent technological developments have made it possible to almost eliminate this concern.

In this chapter, congestion pricing was introduced as a transportation policy without a special emphasis on air pollution reduction effects. Chapter 3 will describe the air pollution impact of road transportation as this thesis tries to study the air pollution impact of congestion pricing and other policies. The concept of transportation demand management (TDM), which includes congestion pricing, will be introduced. Then, in Chapter 4, an idea to modify an ordinary congestion pricing in an attempt to more actively reduce air pollution will be introduced and named "pollution-adjusted-rate congestion pricing".

Chapter 3

Road Transportation and Air Pollution

3.1 Overview

Air pollution is one of the greatest externalities associated with road transportation, and emissions from transportation sources account for a large share of national emissions in several criteria pollutants. Although improvements in vehicle manufacturing technologies have contributed to significantly reducing emission levels of each vehicle, the growth in the vehicle miles traveled (VMT) has offset the improvements. A rise of global environmental problems like global warming by increasing CO_2 emissions has brought a new challenge for transportation planners to reduce travel demand or VMT.

In this chapter, air pollution impacts of road transportation, together with the efforts to reduce them, will be discussed. First, various externalities associated with road transportation, which include air pollution costs, will be discussed in Section 3.2 and the magnitude of the air pollution externality is compared with other externalities such as congestion and accidents.

In Section 3.3, air pollution impacts of road transportation will be discussed, and pollutants in which road transportation has substantially large shares in the national emissions will be examined with their emission trends and formulation mechanisms.

The mechanism of vehicle pollutants formulation is complex, and each pollutant is formed in different operational conditions depending on various factors such as VMT, travel speed, and the number of trips as well as other operational conditions. Models to estimate the relationship between those factors and the levels of emissions have been developed. A model developed by the U.S.

Environmental Protection Agency (U.S. EPA) will be introduced in Section 3.4 as it will be used in the simulations in Chapter 5.

As the levels of vehicle emissions are affected by various factors, so the policies to reduce them can take various forms. Some are taken by environmental regulatory agencies such as the EPA in the United States while others are taken by transportation sectors. From the environmental policy perspective, policies to control vehicle emissions require quite different approaches compared to stationary emission sources like factories or electric power plants. The environmental policies such as vehicle and fuel standards that the United States have taken will be described in Section 3.5.

The main task of transportation sectors has been to expand road capacities to keep up with increasing traffic demand. As road expansions become increasingly difficult partly because of environmental reasons, more emphasis is put on the demand side of transportation. This approach is called transportation demand management (TDM) and will be described in Section 3.6.

3.2 External Costs of Road Transportation

Air pollution is one of the major externalities associated with road transportation. According to economic constructs, external costs can be internalized by charging the costs to the users. In this section, external and internal cost elements of road transportation will be explained, and several estimates for the magnitude of those costs will be introduced.

3.2.1 Cost Elements of Road Transportation

There are costs for driving a car. Some costs are internal in the sense that they are perceived by road users or infrastructure providers. Costs to purchase a car or fuel, or costs to build a highway are examples of internal costs. Others are external in the sense that they are unintended consequences or unintended side effects. External costs are often borne by a broad range of people including non-users. Costs of accidents and environmental hazards are examples. Also, time loss to other users associated with the existence of a certain user is an external cost since it is a "spill over" cost caused by the user and borne by other drivers. The following is a list of cost elements related to road transportation[29]:

1. Internal costs to the road-user
    - Vehicle
    - Fuel
    - Traveling time

- Own risk assumption

2. Internal costs to the infrastructure provider
    - Investments
    - Maintenance
    - Traffic operations and surveillance
3. Costs of external effects
    - Accident costs
        - Material damage
        - Medical care and rehabilitation
        - Loss of production
        - Human pain and suffering
        - Police, rescue services and administration of justice
    - Environmental costs
        - Air pollution (effects on health, growing crops, surface and ground water, and flora and fauna)
        - Noise
        - Vibrations
        - Barrier effects
        - Impact on urban and rural landscapes
    - Congestion costs
        - Time lost by other road users

Among those cost elements, internal costs are perceived by road users or infrastructure providers, who make decision on whether or not they drive, build roads, or do maintenance work and to what extent. In other words, the quantities of those internal cost elements are controlled by their prices or costs. However, the quantities of the external cost elements are not controlled in the same way because external costs are not perceived in the course of decisions by those who make decisions. This is the basis for the need of pricing for the external cost elements. Without appropriate pricing, the quantities of external cost elements exceed economically efficient point just as under priced commodities are excessively traded in the market.

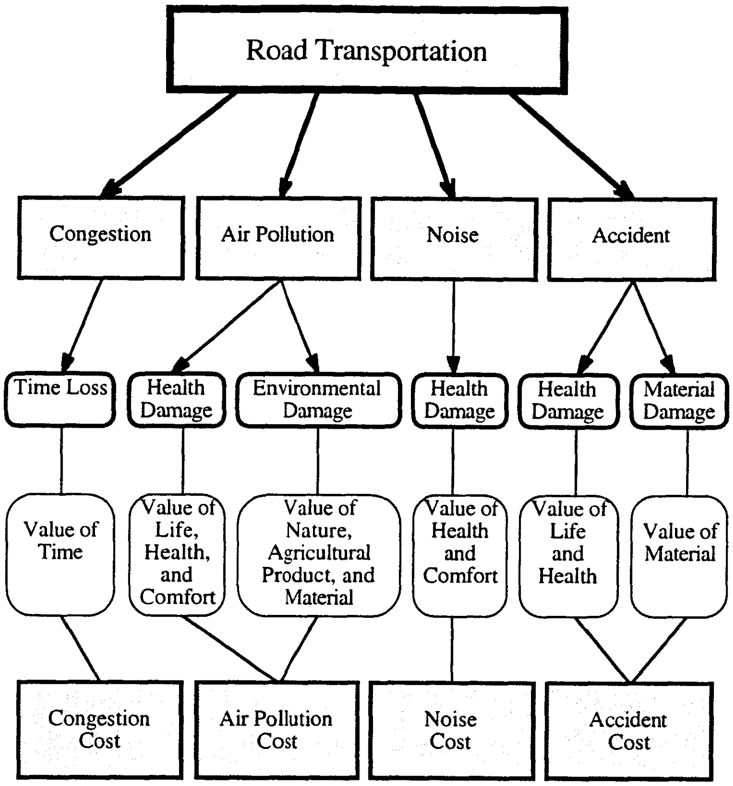

Figure 3-1: External costs associated with road transportation

In the case of traffic congestion, traffic volume (quantity) exceeds the efficient amount if the users are not charged with proper amount of tolls. Pricing will force the volume to stay at the efficient amount, where marginal cost is equal to demand, as was described in Section 2.2.

3.2.2 The Amount of External Costs

In order to set the appropriate price in pricing policies, the amount of external costs must be properly evaluated. However, since they are not priced in the market, the costs need to be estimated. Figure 3-1 illustrates the concept of estimation methods for typical external costs associated with road transportation. In order to estimate the costs, the damages caused by those externalities should be estimated first. Then the costs are estimated applying appropriate values for the damages.

MacKenzie (1992) estimated the economic costs of motor vehicle air pollution in the United States in 1989 to be $10 billion as a conservative estimate[37]. His estimate is based on two other analyses conducted by French (1988) and Sperling and DeLuchi (1989).

French estimated the costs of motor-vehicle generated ozone reflected in health effects, lost labor hours, and reduced agricultural revenues[22]. By projecting French's results, MacKenzie obtained the estimated damages of $9 billion per year with a range of $5 billion to $16 billion for 1989.

Sperling and DeLuchi estimated the costs from motor-vehicle air pollution, including illnesses and premature death, reduced agricultural productivity, damage to materials, reduced visibility, and others[50]. They calculated damages amounting to between $10 billion and $200 billion per year, the large range reflecting the uncertainty surrounding the number of deaths and illnesses attributable to pollution and the monetary value of human health and life.

For the aggregate costs of congestion in the United States, one widely cited figure is the one by the Texas Transportation Institute (TTI)[54], which found that congestion costs for lost time was $28.6 billion in 1987. The General Accounting Office cites estimates of national productivity losses from congestion of $100 billion annually[22], and cites estimates of truck-delay costs from congestion of $24 to $40 billion per year[21].

Kageson (1993) shows results of studies for external costs of transport in percent of Gross Domestic Product (GDP) for European countries (Table 3.1)[29]. These figures include not only road transportation but also other modes, but almost all external costs of air pollution and congestion are caused by road transportation. The estimate of MacKenzie (1992) for the United States is also listed for a comparison.

	Air pollution	Noise	Other e.c.[1]	Accidents	Congestion	Total
MacKenzie, 1992 (U.S.)[37]	0.71%	0.17%	0.48%	1.05%	1.91%	4.32%
Grupp, 1986 (Germany)	0.41%	0.08%	0.08%	0.79%		1.36%
Planco, 1990 (Germany)	0.67%	0.09%	0.18%	1.08%		2.06%
UPI, 1991 (EC)	1.39%	1.98%	3.34%	3.16%		9.86%
ECOPLAN, 1992 (EC)	0.68%	0.52%	0.21%	0.28%	0.07%	1.76%
Infras, 1992 (EC)	0.72%	0.71%	0.47%	0.26%	0.21%	2.36%
CE, 1998 (EC)	0.27-0.38%	0.06%		0.49%	0.14%	1.02%

Table 3.1: Total external costs of transportation in % of GDP

Source: Kageson (1993)[29]

3.3 Air Pollution Impact of Road Transportation

3.3.1 Transportation-Related Pollutants

As is described in Section 3.2, air pollution cost is one of the major external costs associated with road transportation. Although each individual vehicle represents a minuscule part of the cost, the

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[1] Other environmental costs

collective cost from road transportation lies within the range of 0.3% to 1.4% of GDP according to the estimates introduced in Section 3.2. Transportation's share of pollution is significantly large in three criteria pollutants[2]: carbon monoxide (CO), and nitrogen dioxide (NO_2), and volatile organic compounds (VOC) (volatile organic compounds (VOC) and oxides of nitrogen (NO_x) are precursors of ozone.)[3]. Emission trends for these pollutants are shown in Figure 3-2 along with the transportation share of emission.

The CO emissions from on-road vehicles have influenced the national trend. In 1970, the national emissions were around the peak at 128 million short tons[4] of which 69% (88 million short tons) came from on-road vehicles. In 1994, the total emissions had declined by 30 million short tons, of which the reduction in on-road vehicle emissions account for 90% (27 million short tons), despite increases in VMT during the same period.

The share of on-road vehicles in NO_x emissions had declined slightly from 36% in 1970 to 32% in 1994, but the emissions had increased from 7.4 million short tons to 7.5 million short tons during the same period. In 1994, emissions from on-road vehicles and electric utilities each contributed about one-third to the national total.

The national VOC emissions peaked in the early 1970s and had declined since then except for a slight increase in 1993 and 1994. The emissions from on-road vehicles followed a similar pattern, peaking around 1970 and had declined drastically since then, even with the enormous increase in VMT. From 1970 to 1994, on-road vehicle emissions dropped 51%, which is more drastic than the 76% decline in the national emissions.

Mechanism of Pollutants Formulation

Each pollutant is a by-product of different vehicle and fuel characteristics and operational conditions. One of the most influential elements of pollutant formulation is the temperature of combustion reaction, which depends on other factors such as the outside temperature, vehicle travel speed, load, cooling system, and whether the engine has been warmed up. The emission of CO and hydrocarbons (HC) decreases and of NO_x increases as the temperature of combustion reaction increases. This is due to the fact that CO and HC are the products of incomplete combustion of fuels, and NO_x is the product of high-temperature chemical processes that occur during the combustion process itself. This characteristics accounts for the fact that the emission of NO_x per mile of travel increases as

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[2] Criteria pollutants are the ones regulated with National Ambient Air Quality Standards (NAAQS) and include carbon monoxide (CO), oxides of nitrogen (NO_x), volatile organic compounds (VOC), sulfur dioxide (SO_2), fine particulate matter less than 10 microns (PM-10), lead (Pb), and total suspended particulate matter (TSP)[43].

[3] See Appendix A for description on characteristics of these pollutants.

[4] 1 short ton = 0.907 metric ton

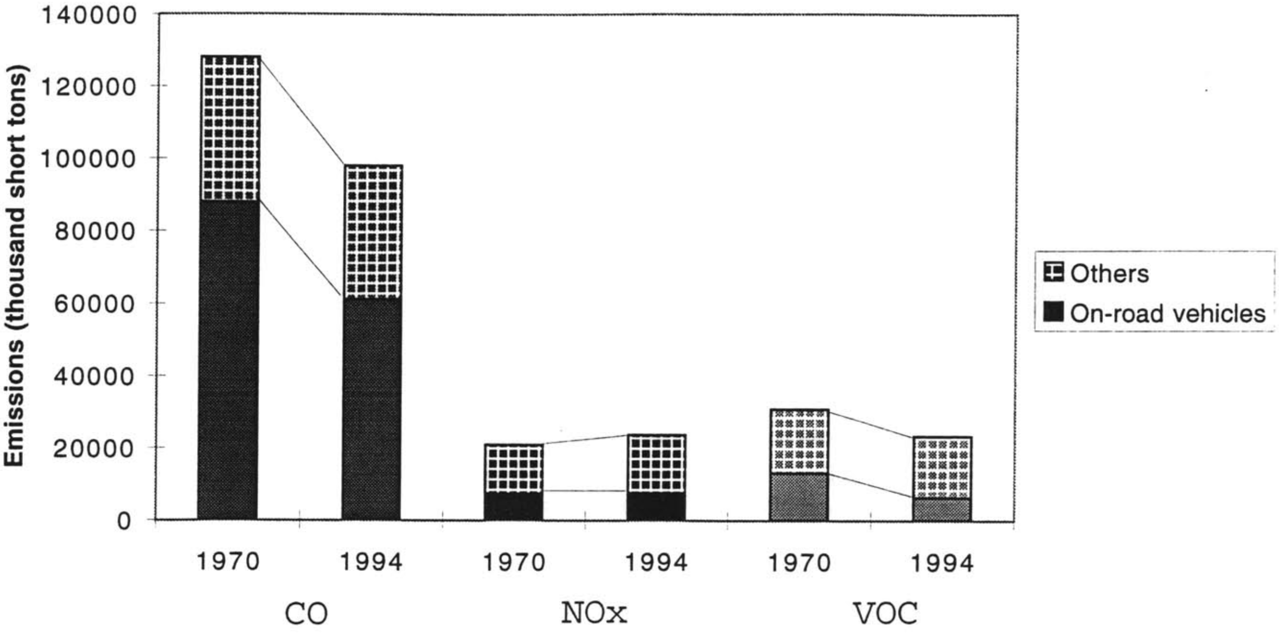

Figure 3-2: Emission trends

Source: EPA (1995)[43]

the average vehicle speed increases at high speed range close to free flow. This relationship between average speed and emission will be described in Section 3.4.

Ozone (O_3) is not emitted directly from combustion process but formed in the air by a chemical reaction involving HC and NO_x in the presence of sunlight. Since too few hours of sunlight remain for the evening rush-hour emissions for the chemical reaction to be completed, graphs of daily O_3 concentrations often exhibit a single peak. Other pollutants like CO, HC, and NO_x normally show two peaks of concentration in urban areas corresponding to the morning and evening rush hours.

Emission characteristics are quite different among different vehicle and fuel types. For example, diesel-powered vehicles emit a substantially higher level of SO_2[5] than gasoline-powered vehicles because of the high sulfur content of diesel fuel. Emissions of other pollutants are also different between the two fuel types and different vehicle types. Figure 3-4 shows the emission shares for four pollutants (CO, NO_x, VOC, and SO_2) of four vehicle types: light-duty gasoline-powered vehicles (LDGV), light-duty gasoline-powered trucks (LDGT), heavy-duty gasoline-powered vehicles (HDGV), and heavy-duty diesel-powered trucks (HDDT).

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[5] Transportation is not a major contributor to emissions of SO_2[16].

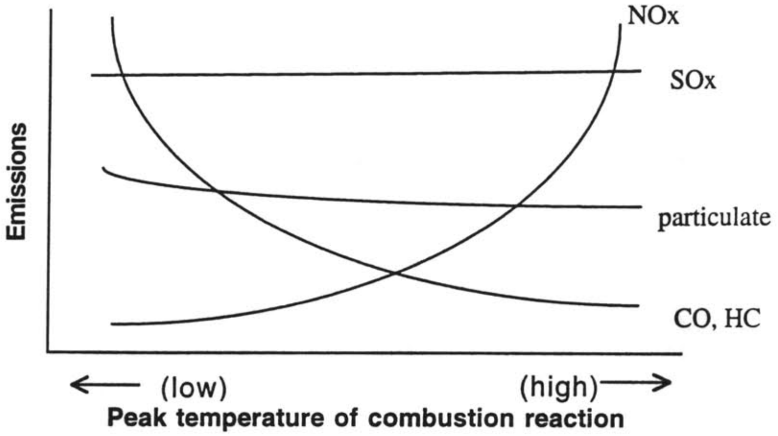

Figure 3-3: Combustion emissions as a function of peak combustion temperatures

Source: Stern et al. (1984)[52]

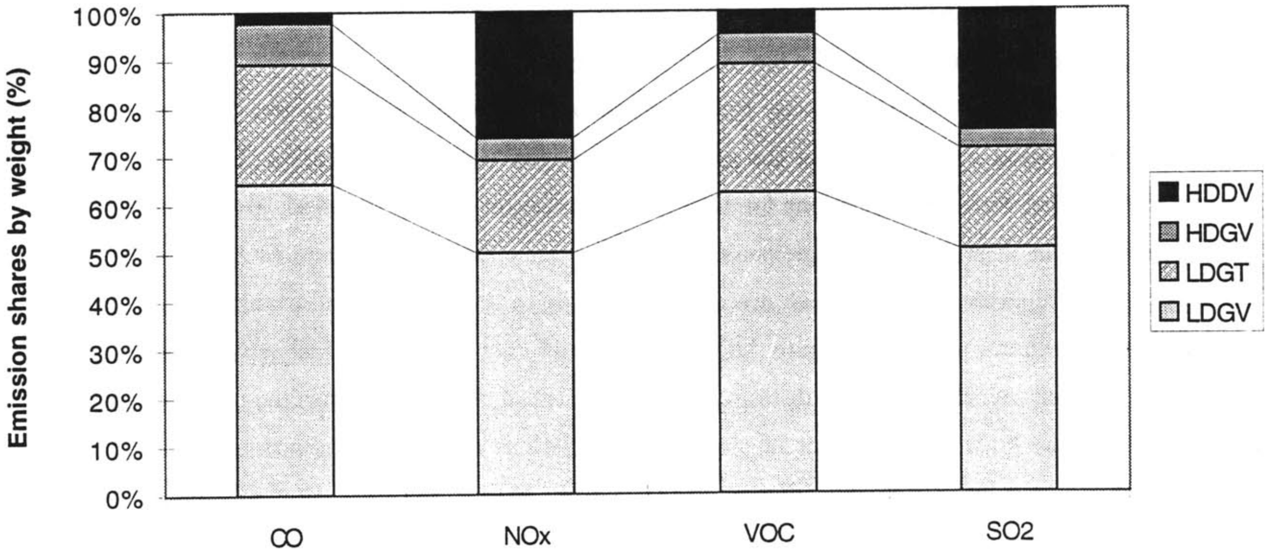

Figure 3-4: Emission shares of four vehicle types

Source: EPA (1995)[43]

3.4 Estimation of Vehicle Emissions

There are several factors that affect the level of vehicle emissions: vehicle and fuel type, vehicle mile traveled (VMT), travel speed, the number of trips, intervals between trips, and outside and engine temperatures[6]. Among these factors, speed is the most important one when the environmental impact of congestion pricing is evaluated since reduced congestion increases the travel speed during rush-hours. Therefore, it is essential to model the relationship between the travel speed and the levels of emissions under various conditions.

3.4.1 Determination of Emission Rates—The Federal Test Procedure

The existing emission models use emission rates derived through the testing of numerous new and in-use motor vehicles under the federal test procedure (FTP)[7]. The FTP consists of a defined set of modal patterns (start, stop, acceleration, deceleration, idling, and constant-speed cruise operations) and is composed of three subcycles, known as the Bag 1, Bag 2, and Bag 3 cycles (emissions are collected in separate sample bags for each subcycle)[25]. Bag 1 is from the cold-start portion, Bag 2 is from the stabilized portion, and Bag 3 is from the hot-start portion of the test. The bag samples are analyzed to determine the average emission rates for the vehicles operating under the test parameters.

3.4.2 The EPA Models

The U.S. EPA has developed a series of computer programs to estimate the emissions of HC, CO, and NO_x from the highway mobile source[8]. The latest version, MOBILE5a[15], was published in 1993, but the accompanying report (AP-42) for MOBILE5a is not published yet[9]. However, the current AP-42 report[17], which is based on MOBILE4, the former version of MOBILE5a, describes the estimating procedures used in the computer programs.

An emission level at a given travel speed is calculated using a speed correction factor (SCF), which relates the emission levels at FTP speed (19.6mph) and the given speed. Travel speed used for this calculation is an average speed under a normal traffic and not a constant cruising speed. However, the distinction between stop-and-go traffic and smooth flow is impossible if they are in the

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[6] Guensler and Sperling (1994)[25] lists a series of parameters known to affect motor vehicle emission rates. This list includes not only the components explicitly included in the EPA model described in Section 3.4.2 but also other components such as road grade and vehicle class.

[7] The procedure is stipulated in the Federal Register, 42 FR 32954, June 28, 1977.

[8] The California Air Resources Board(CARB) has developed a similar model for the use in California, which is called EMFAC[58].

[9] It is scheduled to be published in late 1996.

same average speed.

MOBILE4 Computer Program

The MOBILE computer programs calculate the emissions of HC, CO, and NO_x emitted per vehicle mile for eight types of highway motor vehicles for low and high altitude regions of the United States. The eight vehicle types are: light-duty gasoline-powered vehicles (LDGV), light-duty gasoline-powered trucks I (LDGT1), light-duty gasoline-powered trucks II (LDGT2), heavy-duty gasoline-powered vehicles (HDGV), light-duty diesel-powered vehicles (LDDV), light-duty diesel-powered trucks (LDDT), heavy-duty diesel-powered vehicles (HDDV), and motorcycles (MC).

Emission factors are dependent on a series of assumptions about ambient temperature, fuel volatility level, air conditioning use, loading and trailer towing, and vehicular operating mode, speed, age, and mileage accumulation[8]. The program estimates the mileage accumulation of each model year and the distribution of model years composing the fleet in any calendar year between 1960 and 2020. The emission factors for any model year gradually increase as the ages of vehicles increase because of mechanical deterioration.

Emission factors are calculated as the multiplications of basic emission rates and a series of correction factors that account for variables listed above. The values of basic emission rates and correction factors were determined from the results of the FTP. The general emissions calculation equations have the following form[10]:

$$\begin{aligned} COMP_{pn} &= \sum_{i=n-19}^{n} [TF_{in} \times \{(BEF_{pin} \times SALHCF_{ips} \times RVPCF_p) \\ &\qquad + REFUEL_{ip} + RNGLOS_{ip} + CCEVRT_{ip}\}] \end{aligned} \tag{3.1}$$

where

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[10] These equations are used for LDGV, LDGT1, and LDGT2, but equations for other vehicle types also have similar forms.

i = model year,

n = calendar year of analysis,

p = pollutant (HC, CO, or NO_x),

$COMP_{pn}$ = composite emission factor in g/mile, on January 1 of calendar year,

TF_{in} = fraction of the total miles driven by model year i vehicle,

BEF_{pin} = basic exhaust emission rates in g/mile,

$SALHCF_{ips}$ = composite correction factor,

$RVPCF$ = fuel volatility correction factor (for HC and CO only),

$REFUEL_i$, $RNGLOS_i$, $CCEVRT_i$
= refueling, running loss, and crankcase and evaporative emission factors, respectively (for HC only).

The composite correction factor is determined from the following equation:

$$SALHCF_{ips} = SCF_{ips} * ACCF_i * XLCF_i * TWCF_i * HHH_p \tag{3.2}$$

where

s = average speed in miles/hour,

SCF_{ips} = speed correction factor,

$ACCF_i$ = air conditioning correction factor,

$XLCF_i$ = extra load correction factor,

$TWCF_i$ = trailer towing correction factor,

HHH_p = humidity correction factor (for NO_x only).

Speed Correction Factor (SCF)

Among the correction factors listed above, the speed correction factor (SCF) is the most important one in analyzing the environmental impacts of congestion pricing since an increased travel speed is the major outcome of congestion pricing schemes. Other emission correction factors are also affected as a result of secondary effects such as additional miles driven to avoid priced facilities. However, since this thesis focuses on congestion reductions of a single facility rather than social changes in a whole transportation system or the land use patterns, the speed correction factor plays the major role in the analyses of congestion pricing policies. Thus, the characteristics of the speed correction factor are further described here.

The speed correction factor is used to calculate emission levels in speeds other than the FTP speed (19.6mph). It is determined from the following equation:

$$SCF_{ips} = \frac{SF(s)}{SF(sadj)} \tag{3.3}$$

where

$$SF_{ip}(s) = \begin{cases} A_{ips}/s + B_{ips} & \text{for } p = HC \text{ and } CO \\ \exp(A_{ips} + B_{ips} \cdot s + C_{ips} \cdot s^2) & \text{for } p = NO_x \end{cases} \tag{3.4}$$

where A_{ips}, B_{ips}, and C_{ips} are constants that vary with i, p, and s. The variable *sadj* is the FTP speed (19.6mph) adjusted for cold-start and hot-start fractions of VMT:

$$sadj = \frac{1}{\frac{w+x}{26} + \frac{1-w-x}{16}} \tag{3.5}$$

where w and x are the fractions of VMT in hot-start and cold-start modes, respectively. For the FTP, the test vehicle spends 20.6% of VMT in cold-start operation (Bag 1), 52.1% in stabilized operation (Bag 2), and 27.3% in hot-start operation (Bag 3). The average speed used for cold-start and hot-start operations is 26mph, and the average speed for hot-stabilized operation is 16mph. Thus, the overall average speed for all three operation modes in the FTP is 19.6mph, and it should be adjusted according to the fraction of cold-start and hot-start operations of local data.

The speed correction factor is only valid for speeds in the 2.5mph through 55mph range since the regression equations used to obtain coefficients were based on speed data in that range[11]. The speed correction factors for LDGV are shown in Figure 3-5.

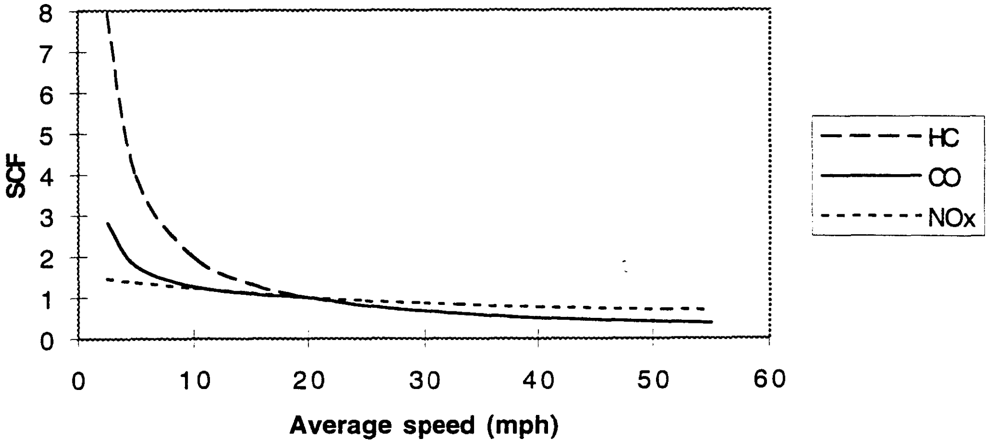

Figure 3-5: Speed correction factors for LDGV (model year 1995)

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[11] In MOBILE4.1, a revised version of MOBILE4, this range was extended to 2.5mph through 65mph incorporating four new test results with average speeds of 48, 51, 58, and 64 mph[8].

It can be seen that the SCF for NO_x does not decrease much even under a high travel speed range around 50mph. In some other vehicle types, this is more obvious and the SCF may even go up as travel speed increases. This characteristics can be explained by the mechanism of the pollutant formation mechanism. As is described in Section 3.3, NO_x emission increases as the temperature of combustion process goes up. Therefore, high temperature of engines under high travel speeds emits higher levels of NO_x.

3.5 Environmental Policies for Air Pollution Reduction

The United States has developed several environmental policies to reduce air pollution from vehicles. Transportation pollution sources, or vehicles, are often called "mobile" sources as opposed to "stationary" sources such as factories and electric power plants. In this section, environmental policies, or those mainly taken by environmental sectors of governments like the U.S. EPA, will be explained in two categories: vehicle emission standards and fuel standards. Later, transportation policies, or those mainly taken by transportation sectors of governments like the DOT, will be explained in Section 3.6

3.5.1 Characteristics of the Problems

Although road transportation contributes substantially to generation of several pollutants (Figure 3-2), the mobility of the source (vehicles), an intrinsic characteristic of transportation, makes control policies difficult and different compared to the ones for what is called stationary-source pollution such as factories or electric power plants emissions.

Mobility has two major impacts on policy. On the one hand, pollution is partly caused by the temporary location of vehicles, and they have to be there with travelers. Therefore, relocating them is not as viable a strategy as relocating electric power plants. On the other hand, it is more difficult to tailor vehicle emission rates to local pollution patterns since any particular vehicle may end up in many different urban and rural areas during the course of its useful life.

Mobile sources are also much more numerous than stationary sources. While there are approximately 27,000 major stationary sources[12], more than 190 million vehicles[13] exist in the United States. As the number of sources being controlled increases, enforcement becomes more difficult. In addition, vehicles are usually run by amateurs unlike stationary sources, which are generally run

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[12] This figure is taken from Tietenberg (1996)[55]

[13] This figure includes 146 million automobiles, 4 million motorcycles, 0.6 million buses, and 47 million trucks (U.S. DOT, Bureau of Transportation Statistics; 1993 figures).

by professional operators and managers. Under amateur operations, emission control is likely to deteriorate over time due to a lack of dependable maintenance and care.

3.5.2 Vehicle Emission Standards

The U.S. approach for vehicle emission standards consists of emission standards for new vehicles and for vehicles in use. New vehicle emission standards are administered through a certification program and an associated enforcement program. The inspection and maintenance (I&M) programs are used to deter tampering and to encourage regular routine maintenance of vehicles in use.

Certification Program

The certification program tests prototypes of car models for conformity to federal standards. Only engine families with a certificate of conformity are allowed to be sold. The federal standards were first set by the Clean Air Act Amendments of 1965 for HC and CO emissions to take effect during 1968. The impetus for this act partly came from the automobile industry out of a fear that every state would pass its own unique set of emission standards. As a result, the law prohibits all states except California from setting their own standards. Standards for other pollutants were added afterwards: for evaporative hydrocarbons in 1971, for NO_x in 1973, and for particulates in 1982[14], and the standards have been tightened substantially over the years. The tailpipe emissions have been reduced by 91% for HC, by 96% for CO, and by 85% for NO_x compared to an uncontrolled 1971 vehicle[31].

Tietenberg (1996) points out that the U.S. national emission standards are too stringent and that the uniformity of the standards together with the stringency is causing an economic inefficiency. A uniform standard cannot be cost-effective because cost-effectiveness requires higher control costs in areas having real difficulty in meeting the ambient standards than the rest of the country. Tietenberg argues that the controls are too stringent primarily because of the uniformity of the standards, which requires vehicles not contributing to nonattainment to bear the same cost of controls as those that do contribute[55].

Associated Enforcement Programs

The certification program is complemented by an associated enforcement program which contains assembly line testing, as well as recall and anti-tampering procedures and warranty provisions. The EPA tests a statistically representative sample of assembly line vehicles to ensure that the prototype

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[14] These years are based on the case of light-duty vehicles. For details of the changes or for the case of heavy-duty vehicles, See EPA, 1991[17].

vehicles are representative. If the tests reveal that vehicles do not conform with federal standards, the certificate may be suspended, or the manufacture may be ordered to recall and remedy manufacturing defects that cause emissions to exceed federal standards.

Two separate types of warranty provisions are required by the Clean Air Act . They are designed to ensure manufactures' incentive to produce a vehicle which will meet emission standards over its useful life if it is properly maintained.

Inspection and Maintenance (I&M) Program

The objective of the I&M program is to identify vehicles that are violating the standards and to bring them into compliance, to deter tampering and to encourage regular routine maintenance. A shorter and less expensive procedure than the FTP is used because the FTP is too expensive to be used on a large number of vehicles.

Because of the expense and questionable effectiveness of the program, it is one of the most controversial components of the policy package used to control mobile source emissions[55]. The cost per ton of reduction from the I&M program turns out to be two to three times higher than that for securing an equivalent reduction from stationary sources[47]. In cost-benefit analyses, the net benefits of the I&M program turn out to be negative in some geographic areas. A study of the Maryland inspection program estimates a benefit-cost ratio to be around 0.125[38].

3.5.3 Fuel Standards

Lead Phaseout Program

EPA has reduced the amount of airborne lead by ensuring the availability of unleaded gasoline. Under Section 211 of the Clean Air Act, EPA was provided with the authority to regulate lead and any other fuel additives used in gasoline. Under this provision gasoline suppliers are required to make unleaded gasoline available. Penalties are assessed on distributors for supplying catalyst-equipped vehicles with leaded gasoline since catalytic converters are damaged by lead.

In 1985, EPA issued a new, more stringent regulation on lead in gasoline. This regulation required a large amount of reductions on the lead content in gasoline by specific deadlines. Recognizing that the costs to meet the goals and deadlines were substantially different from one refiner to another, EPA initiated the lead phaseout program to provide additional flexibility in meeting the regulation. The idea behind it was that the excess lead introduced by those complying late would be offset by those complying early.

The lead phaseout program used a design similar to the emissions trading program later used in the 1990 Clean Air Act Amendments[15]. Refiners reducing more lead than required by the applicable standard in each quarter of the year can bank the credits for use or sale in some subsequent quarter. Also, banked credits are transferable among refiners. The lead rights program was designed only as a means of facilitating the transition to the lower standards and ended by December 31, 1987 as scheduled.

Those policies towards airborne lead reduction have been quite successful and the emission of lead has been reduced substantially (Figure 3-6).

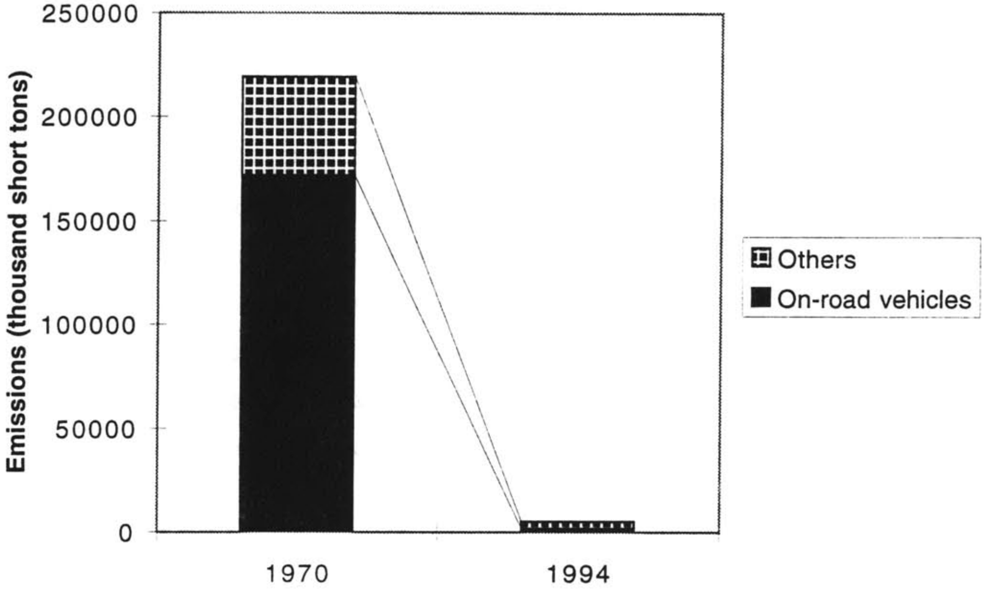

Figure 3-6: Lead emission trend

Source: EPA (1994)[16]

Alternative Fuels

Congress and some states have passed legislation attempting to encourage the development of alternative fuels such as methanol, electricity, and hydrogen and of cleaner gasoline. The 1990 Clean Air Act Amendments mandate the sale of cleaner burning reformulated gasoline in certain CO and severe O_3 nonattainment regions[14]. The 1992 Energy Policy Act requires the federal government and some private fleet owners to purchase alternative fueled vehicles. By 1996, one-fourth of all new federal cars and light trucks have to run on alternative fuels.

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[15] The 1990 Clean Air Act Amendments established a large-scale system of tradable emission permits to control SO_2 emissions that generate acid rain[14, 30].

California has passed a more progressive legislation. In September 1990, the California Air Resources Board (CARB) passed its Low Emission Vehicles (LEV) and Zero Emission Vehicles (ZEV) regulations. The former requires increasingly stringent emissions standards over time for conventionally fueled vehicles. The latter mandates that at least 2% of new cars and light trucks sold by 1998 in the state must be ZEVs[16]. This percentage rises to 5% by 2001 and 10% by 2003. Currently the focus for meeting this requirement is on electric vehicles, but hydrogen-powered vehicles may qualify if they become commercially viable[55].

While policies have been formulated around the development of alternative fuels, the cost-effectiveness of these policies is not clear. Walls and Krupnick (1990)[63] examined the cost-effectiveness of methanol vehicles by projecting both costs and emissions reductions for the years 2000 through 2010 and calculating costs per ton reduced. The calculated costs were very high, almost five times as high as alternative means of reducing hydrocarbon emissions.

3.6 Transportation Policies for Air Pollution Reduction

Transportation policies cannot be independent from environmental concerns as the air pollution and other environmental damages from transportation become increasingly serious. At the early stages of the environmental movement, transportation sectors tried to maintain transportation infrastructure developments believing that enhanced mobility and reduced congestion would help reduce air pollution. In other words, they tried to increase the supply of transportation in order to keep up with the growing demand. However, as this supply-side approaches started to be challenged by environmental advocates, the concept of transportation demand management (TDM) has been gaining its importance.

3.6.1 Limits of Road Infrastructure Development

Road infrastructure developments such as road construction and traffic signalization have been believed to have positive impact on air quality. They have been expected to increase travel speed and eliminate congested traffic conditions that cause excessive air pollution. In general, a vehicle running at higher speeds emits less emissions than a vehicle in a more congested situation in the course of their trips.

However, this air quality rationale for highway expansions is often questioned based on several reasons. First, emissions of NO_x rise with rising speeds at a speed close to free-flow speeds as

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[16] ZEVs are defined as vehicles which directly emit no VOCs, NO_x, or CO; any indirect emissions from producing the electricity are not counted.

described in Section 3.4. Secondly, a reduced travel time usually attracts new travelers (latent demand) making the congestion situation no better than before. Furthermore, Kessler and Schroeer (1995) point out that reductions in running emissions due to an increase in vehicle speed contribute little to the overall emissions reduction since the portion of running emissions is declining as opposed to the emissions from the number of trips[31]. Figure 3-7 shows the portions of emissions attributable to number of trips and vehicle miles traveled (VMT). Amounts of cold & hot starts and hot soak emissions are a function of the number of trips because they are emitted by fixed amounts every time vehicles are used, but amounts of running loss and stabilized exhaust emissions are more or less proportional to VMT.

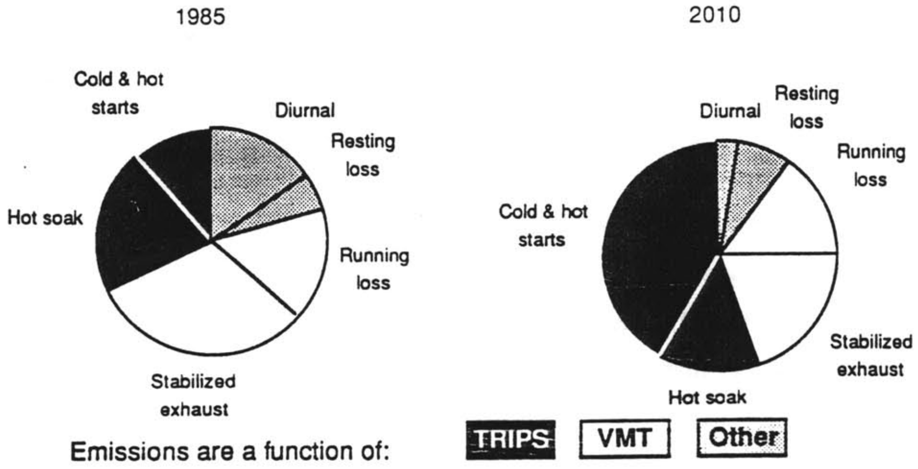

Figure 3-7: The growing importance of trips in auto emissions

Source: Kessler and Schroeer (1995)[31]

Because of the above reasons, the importance of transportation demand management (TDM) has been recognized instead of those supply side approaches like infrastructure development.

3.6.2 Transportation Demand Management (TDM)

Infrastructure development described in the previous section is an approach from the supply side of transportation in the sense that they attempt to increase capacities of transportation infrastructure, or transportation supply. However, the environmental effects of those supply side approaches are limited because of the reasons described in Section 3.6.1, and instead transportation demand management (TDM) has attracted greater attention from transportation sectors in the U.S. and many other countries.

The concept of TDM is illustrated in Figure 3-8. The conventional approach from the supply-side is to balance the increasing demand, A_1 in the figure, by expanding the supply from T_0 to T_1. In contrast, TDM aims at the demand side and has two approaches. The first is a direct, short-term approach: for example, spreading peak traffic over longer time periods, preventing high traffic concentrations from heading towards the same directions, and modal shift, which means encouraging users to switch to alternative modes of transportation. This first approach corresponds to the contraction of A_1 to A_2 in the figure. The second approach emphasizes long-term issues that comprise the sources of transportation demand such as land use and location of urban activity. This second approach of TDM is represented by the shift of the fulcrum in the figure.

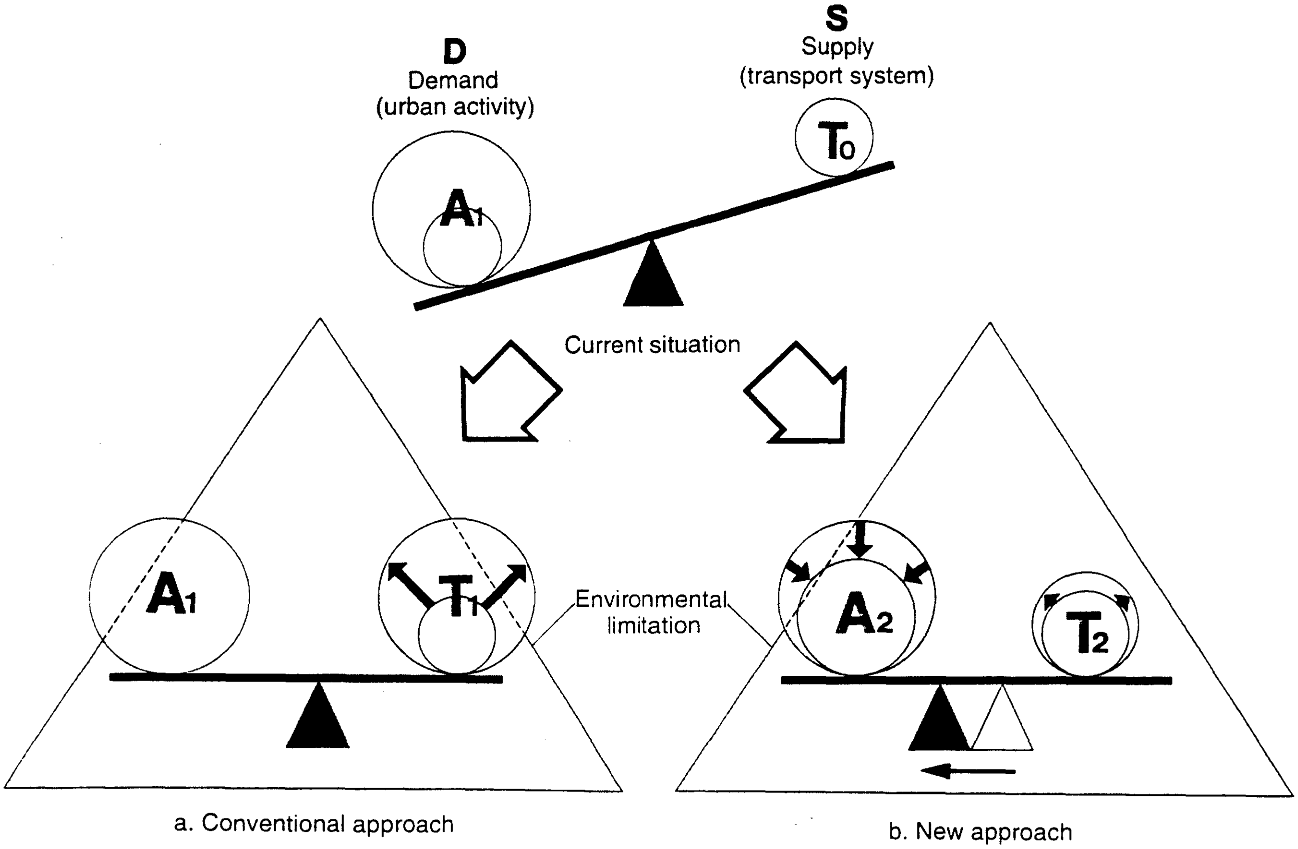

Figure 3-8: The concept of transportation demand management (TDM)

Source: Ohta and Doi (1995)[44]

TDM measures can take a variety of forms. In a broad definition, TDM includes measures that are not directly linked to transportation policies such as: (1) land-use and location management for firms and households such as land-use control and economic development management, and (2) management of activities of firms and individuals such as promotion of flexible working schedules and telecommuting.

TDM measures more directly linked to transportation policies can be categorized into the following groups[59]:

economic instruments e.g. road pricing, road user charges (on vehicles ownership or vehicle use)

regulatory measures e.g. parking controls, area bans, traffic controls for priority of public transport, licensing of drivers

physical restraints e.g. traffic cells.

Congestion pricing is one form of road pricing using economic instruments. As described in Chapter 2, this measure has been studied intensively and introduced in some countries. In the United States, its great potential has started to be well-recognized, and several pilot projects are underway under the Intermodal Surface Transportation Efficiency Act (ISTEA).

3.7 Summary

As this thesis tries to evaluate the air pollution impact of congestion pricing policies, this chapter reviewed the current status of air pollution from road transportation, followed by the policies that have been taken to reduce emissions.

First, various external costs of road transportation, including air pollution costs, were discussed; and some estimated figures for their amounts were introduced. Then, road transportation shares of emissions were discussed, and a model to estimate vehicle emissions was introduced. This model, called the EPA MOBILE model, will be used in a series of simulations in Chapter 5. Finally, environmental and transportation policies to reduce air pollution, including a new transportation policy called transportation demand management (TDM), were described. TDM is gaining increasing attention not only for its potential in transportation improvement but also for its potential in air pollution reduction. Congestion pricing is categorized as one of the economic instruments within TDM.

As described in Section 3.2, the external cost of air pollution, as well as the cost of congestion, needs to be internalized in order to achieve an economic efficiency. Since vehicle emissions vary depending on travel speed as shown in Section 3.4, they are related to the level of congestion to a certain degree. Section 3.4 also showed that each vehicle emits different levels of emission depending on its vehicle or fuel type. As a way to achieve both air pollution reduction and congestion reduction at the same time, the next chapter proposes a congestion pricing scheme that is different from ordinary congestion pricing schemes. This is called "pollution-adjusted-rate congestion pricing" and will be introduced in Chapter 4.

Chapter 4

Pollution-Adjusted-Rate Congestion Pricing

4.1 Idea and Concept

Among the various costs associated with road transportation, congestion pricing targets mainly the congestion costs, or time lost by other road users. It can be seen in the fact that the pricing theory that justifies congestion pricing is designed to internalize the congestion costs (the costs a given driver causes to others). However, the environmental externality, especially air pollution costs, is strongly related to the existence of congestion in urban areas, and potential environmental benefits from congestion pricing policies are often discussed[1].

The idea of pollution-adjusted-rate congestion pricing is to actively reduce air pollution—not only as a byproduct of congestion reduction—by charging different prices on vehicles depending on their pollution impacts. Thus, even without changing the congestion characteristics, such as traffic volume and travel speed, air pollution reduction could be achieved by changing the composition of vehicles during congested periods. In other words, by forcing "dirtier" vehicles out of congestion and letting them drive through smoother traffic flow, overall air pollution could be reduced.

Emission impacts of vehicles depend on several factors, such as: fuel type (gasoline, diesel, methanol, electric, etc.), vehicle type (automobile, light-duty truck, heavy-duty truck, etc.), vehicle age, mileage accumulation, and maintenance conditions. Theoretically, each vehicle has different emission characteristics and must be charged with different amount of tolls depending on them.

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[1] See Wachs (1992)[62] for the case of California.

However, in practical applications, vehicles must be divided into several groups depending on their emission impacts in order to avoid a complexity in toll collection and make the pricing scheme more comprehensive to users.

Recent developments in zero-emission vehicle (ZEV) technologies—usually electric vehicles—will provide more potential for this pricing scheme. Since ZEVs are emission free, the existence of congestion does not force them to generate additional emissions. Therefore, if this pricing scheme changes vehicle composition in the way that numbers of these "cleaner" vehicles during congested periods are increased, the negative impact of congestion would be mitigated. In an extreme case for example, if all the vehicles during congested periods were ZEVs, the existence of congestion would not cause any additional air pollution.

4.2 Pricing Theory

The pricing theory behind the concept of pollution-adjusted-rate pricing follows the same logic as the one for ordinary congestion pricing. Basically, the optimal toll is the difference between the privately perceived cost and the social cost, and it tries to internalize externalities associated with driving[2]. As traffic volume increases and travel speed decreases, emission levels become greater. Greater emission levels associated with congestion impose higher cost to the society, which is an external cost to the society since it is not perceived by each driver as he makes a decision of making a trip.

This external cost is greater for vehicles with higher emission levels, such as old vehicles and trucks, and the difference generally becomes larger as the traffic volume increases due to greater impact on those high-emission vehicles under congestion. Therefore, the social cost of these "dirtier" vehicles are greater than it is for "cleaner" vehicles. A conceptual illustration of the relationship between traffic volume and social and private costs are drawn in Figure 4-1.

The optimal toll to internalize the air pollution cost is the difference between the social cost and the private cost. As is illustrated in Figure 4-2, the optimal toll (τ) is greater for "dirtier" vehicles ($\tau_d > \tau_c$) and increases as the traffic demand increases ($\tau_2 > \tau_1$).

If the above toll is applied to a typical peak-hour traffic with a traffic volume variation shown in Figure 4-3-a, the optimal tolls for dirty vehicles and clean vehicles have shapes as shown in Figure 4-3-b.

In practice, congestion pricing programs usually charge users with fixed amount of tolls for each

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[2] It was defined mathematically in Equations 2.10 and 2.11, and graphically illustrated in Figure 2-4 for ordinary congestion pricing.

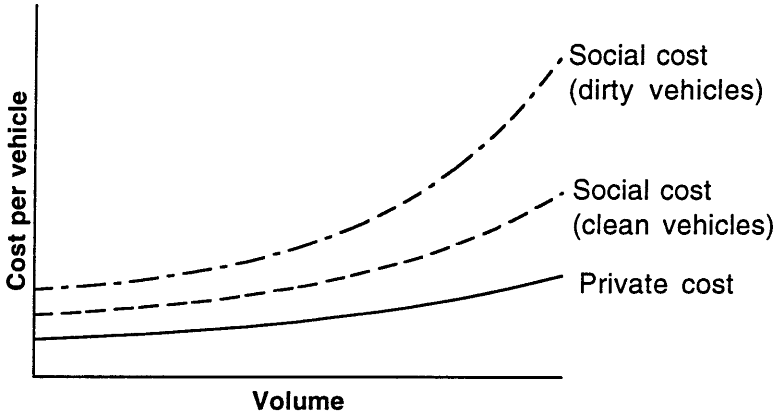


Figure 4-1: Air pollution costs

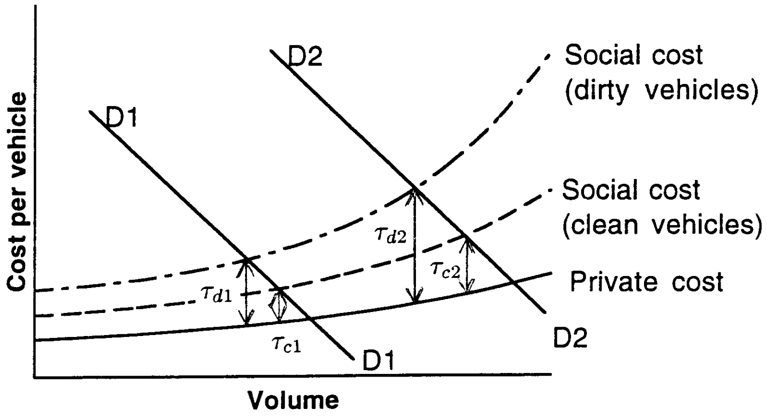
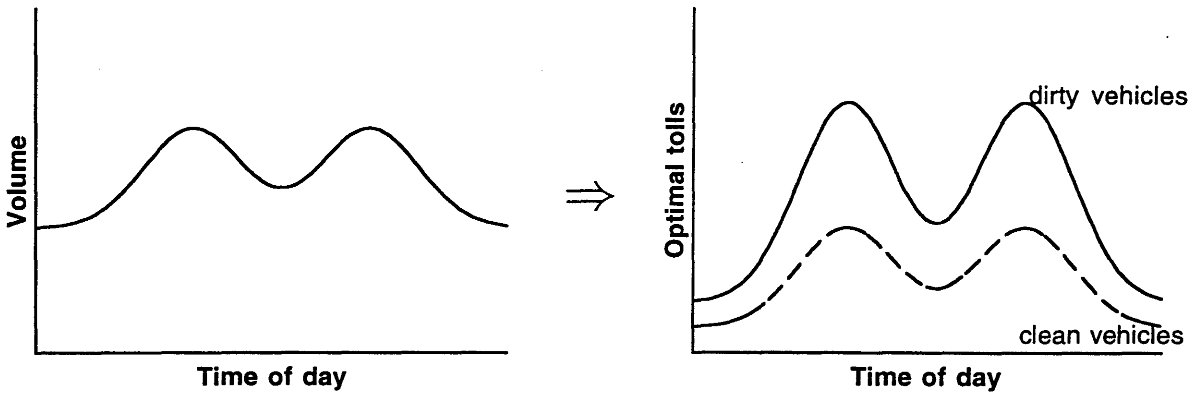


Figure 4-2: Optimal tolls to internalize air pollution costs



a. A typical traffic-volume variation

b. Optimal tolls for dirty and clean vehicles

Figure 4-3: Optimal tolls for a typical volume variation

time period, and the fees change discretely at the boundaries of time zones. In such a case, toll variation would be discrete as shown in Figure 4-4 instead of the continuous variation as shown in Figure 4-3.

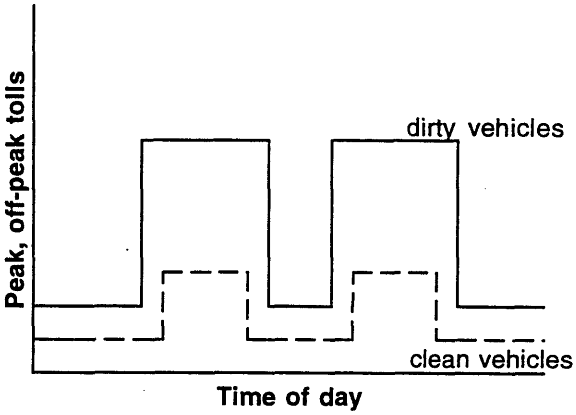


Figure 4-4: Discrete pricing scheme for "dirty" and "clean" vehicles

4.3 Application and Possibilities

There has not been any practical applications of pollution-adjusted-rate congestion pricing. However, recent developments in electronic toll collection (ETC) systems have made this pricing scheme more attractive and feasible. First, as is described in Section 2.3.1, the ETC technology makes it possible to collect tolls from users without having to stop vehicles. Therefore, additional emissions from deceleration and acceleration at toll booths, which sometimes becomes a stumbling block for congestion pricing introduction, can be eliminated. Secondly, automatic vehicle identification (AVI) technology, which supports ETC, brings a great feasibility to the pollution-adjusted-rate pricing. Since vehicles are charged with various amounts of tolls depending on their pollution impacts and time of travel, this pricing scheme requires more detailed identification of vehicles than ordinary pricing schemes. The AVI technology deals with vehicle identifications automatically by reading the information stored in a transponder mounted on each vehicle and makes it possible to charge different amounts of tolls on each vehicle type.

Although this pricing scheme brings additional emission reduction benefits than ordinary congestion pricing scheme in most cases, it may not be as effective as it looks in some cases. Generally, air pollution costs increase as traffic becomes heavy and travel speed declines. However, for some pollutants—especially nitrogen of oxides (NO_x)—within some travel-speed range, the emission level per unit distance traveled increases as travel speed increases, which contradicts with the assumption behind this pricing theory. Therefore, careful assessments on traffic conditions are necessary in order to maximize the benefits from this pricing scheme.

There is another concern on a practical implementation of this pricing scheme—an issue of equity. As owners of old vehicles, which are more heavily charged in this scheme, are more likely to be low-income people, the impact on those people may be greater than ordinary congestion pricing schemes. Thus, collateral actions (combining this pricing scheme with other policies using its revenues) that mitigate the negative effects on low-income people must be considered to increase the political feasibility.

In the next chapter, air pollution impact of this pricing scheme, as well as ordinary congestion pricing schemes, will be simulated. Other transportation policies will also be simulated for comparisons. However, political issues like the issue of equity are beyond the scope of simulation and will not be simulated in any form.

Chapter 5

Policy Simulations

5.1 Overview

In this chapter, the effects of congestion pricing policies on air pollution reduction will be simulated using a macroscopic model. The objective is to come up with some rough estimates in an attempt to provide readers with some ideas on environmental effects of pricing policies. Besides two types of congestion pricing policies—ordinary pricing and pollution-adjusted-rate pricing—three other policies will also be simulated with their emission reduction impacts for a comparison.

The simulation framework will be described in Section 5.2, followed by an explanation of the model that has been designed to simulate the reaction to pricing in Section 5.3. The simulation results will then be presented in Section 5.4. Finally, Section 5.6 will give some analyses and summarizes the chapter.

5.2 Simulation Framework

In this chapter, changes in emission levels caused by congestion pricing and other policies will be simulated. Since the base case traffic volume is taken from the data for a highway near Washington D.C. as a typical variation, the simulations can be interpreted as a case for a point pricing. However, since the emissions from alternative routes are not considered, the situation matches more closely to a zone pricing, charges for distance traveled, or congestion-specific charges[1], in which users cannot simply take alternative routes to avoid tolls. All the calculations are made on per unit distance (per

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[1] Descriptions on these design options were given in Section 2.3.2.

mile) basis[2] so that they can be interpreted in either way.

Emission levels are calculated as of January 1, 1996 for hydrocarbons (HC)[3], carbon monoxide (CO), and oxides of nitrogen (NO_x). Congestion pricing and other policies are assumed to affect the emission levels by changing the following three factors: traffic volume, travel speed, and vehicle composition. As illustrated in Figure 5-1, changes in emission levels are simulated by calculating these three factors both in the base case and under a given policy.

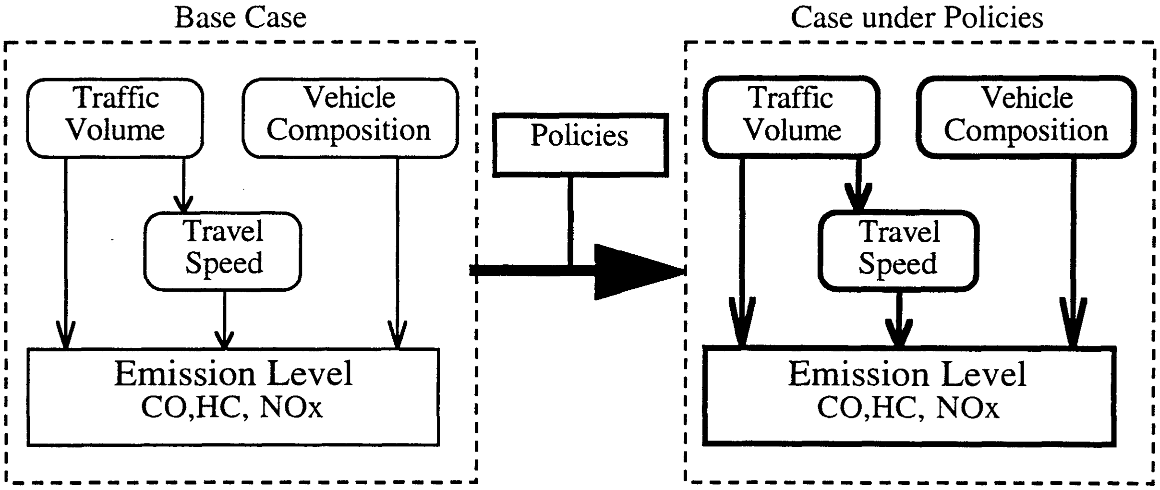

Figure 5-1: Simulation framework

In this section, basic assumptions on these three factors and other factors will be described in Section 5.2.1. The policies to be simulated will then be described in Section 5.2.2

5.2.1 Basic Assumptions

Traffic Volume

The base-case traffic volumes are taken from the data on Chain Bridge Road (VA 123) just inside the Capital Beltway near Washington D.C.[4][40]. It is taken as a typical traffic volume variation showing a morning peak, and does not mean the following simulations test the effects of congestion pricing policies on this highway in particular.

Simulations are run for the time period of 6:15 a.m. to 10:00 a.m., which includes the morning peak hours; and it is divided into 15 time zones, each with 15 minutes. The base-case volume is

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[2] Emissions are calculated in gram/mile, and tolls and initial costs of driving are given by $/mile.

[3] Hydrocarbon emissions calculated in this chapter are non-methane hydrocarbon emissions, but they include ethane, which is excluded in the definition of volatile organic compounds (VOC) by the U.S. EPA.

[4] The original data were given for 30-minute time periods, but they were split into 15-minute periods for this simulation by taking the average volume of two adjacent periods as the the volume of the inserted period. For example, the volume of 6:45 a.m. is the average of the volumes of 6:30 a.m. and 7:00a.m.

shown in Figure 5-2. Volume is measured in passenger cars per hour per lane (pcphpl), and the labels on the horizontal axis indicate the time at the end of each period. Therefore, 6:30 is for the period of 6:15a.m. to 6:30 a.m.

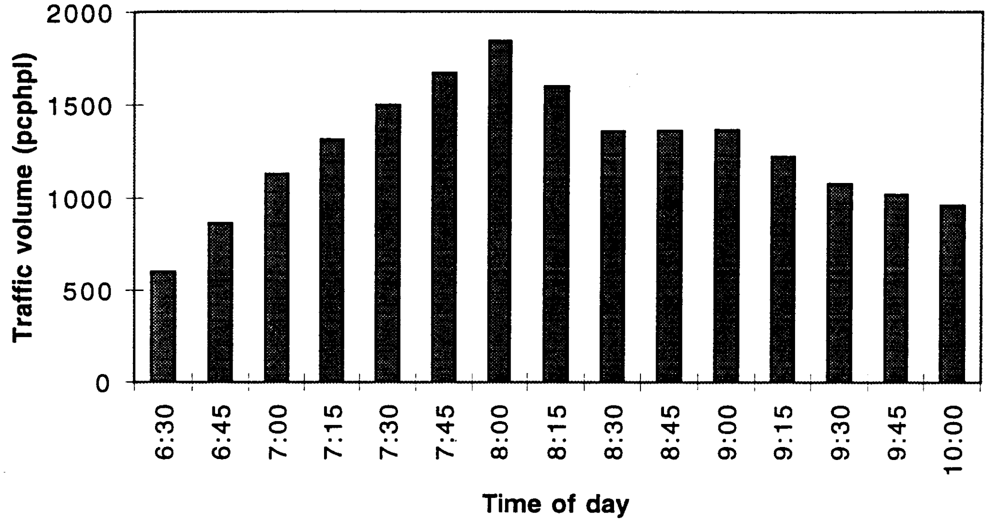

Figure 5-2: Base-case traffic volumes

Travel Speed

The relationships between volume and travel time were introduced in Section 2.2.1, and they are used to calculate the travel speed from the traffic volume. In the simulations, the power function (Equation 2.2 is used with the parameters proposed by Dowling and Skabardonis (1992)[13] as a revised BPR (Bureau of Public Roads) curve. It has the following form:

$$\text{(travel speed)} = \frac{\text{(free-flow speed)}}{1 + \left(\frac{V}{C_p}\right)^4} \tag{5.1}$$

where V is volume and C_p is practical capacity. Practical capacity is assumed to be 2,000 vehicles (passenger car equivalent) per hour per lane in the simulations.

Traffic Composition

The composition of traffic by vehicle type and age is reduced to nine representative groups: light-duty gasoline-powered vehicles (LDGV) with 2, 6, and 12 years in age; light-duty gasoline-powered trucks (LDGT) with 2, 6, and 14 years in age; and heavy-duty diesel-powered vehicles (HDDV) with

2, 6, and 14 years in age. The simplification is based on the national VMT[5], and the simplified vehicle composition is shown in Table 5.1.

vehicle type	2 year old	6 year old	12 year old	14 year old	total
LDGV	19.41%	25.67%	17.47%		62.56%
LDGT	10.92%	12.17%		8.14%	31.23%
HDDV	2.17%	2.42%		1.62%	6.21%
total	32.50%	40.26%	17.47%	9.76%	100.00%

Table 5.1: Simplified vehicle compositions

Other Assumptions

Other assumptions are made on basic conditions:

- Ambient temperature is 75°F.
- The portion of cold-start and hot-start operation is 20.6% and 27.3%, respectively (FTP[6] condition).
- Perceived driving cost is \$0.25/VMT[7].

5.2.2 Simulated Policies

The base case emissions are calculated on the the basis of the above input data and assumptions about conditions. Then the following environmental and transportation policies were considered to test the impacts on emissions of those policies:

1. Ordinary congestion pricing
2. Pollution-adjusted-rate congestion pricing

   Under this congestion pricing policy, higher tolls are charged during the peak period as they are under ordinary congestion pricing, but the tolls are higher for "dirtier" vehicles, such as heavy trucks or old vehicles.

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[5] The national VMT for each vehicle type and age was estimated from Davis (1995)[9], U.S. DOC (1995)[10], and FHWA (1995)[18]

[6] See Section 3.4.1 for descriptions on FTP.

[7] Bhatt (1994) reports that the typical perceived driving costs in the metropolitan Washington region to be on the order of \$0.20 to \$0.30/VMT[3].

3. Reducing numbers of old vehicles

   This simulates a policy sometimes called “early retirement” or “klunker” programs, in which some portion of older vehicles are either bought up by the government or given a strong incentive to retire.

4. Demand reduction

   This corresponds to policies that reduce the overall traffic demand, such as public transportation improvement, license plate restriction, and ride-share promotion.

5. Introduction of zero-emission vehicles (ZEVs)

   Introduction of ZEVs, such as electric vehicles and hydrogen-powered vehicles, which emit no VOC, NO_x, or CO is simulated.

The introduction of the above policies are assumed to change some or all of the three determinants of emission levels: traffic volume, travel speed, and vehicle composition as explained at the beginning of this section. For example, an ordinary congestion pricing policy affects traffic volume, which brings changes in travel speed; while a pollution-adjusted-rate congestion pricing policy changes the vehicle composition in addition to the other two factors by charging different amounts of tolls to each vehicle type.

5.3 Pricing Model Structure

The reaction of road users to a congestion pricing policy is complex and more difficult to simulate than the one to an ordinary toll, in which users are charged with a fixed amount of toll regardless of time of day. The difficulty is caused by the fact some users shift their time of travel if the amount of toll varies depending on time. This thesis attempts to simulate this “time-shifting” behavior using a concept named “avoidance elasticity”. This modeling attempt will be explained in this section. It starts with explanation of direct price elasticity, which is commonly used to simulate reactions to pricing policies, to describe the concept of elasticity and to show why it is not directly applicable to congestion pricing policies.

5.3.1 Direct Price Elasticity

In order to simulate the air pollution impacts of congestion pricing, it is necessary to simulate the road users’ reaction to pricing schemes. For macroscopic simulations of transportation pricing policies, direct price elasticities are commonly used to simulate traffic reduction due to an increase in costs[35, 3]; as a result, various data from actual policy surveys or disaggregate model simulations are available[7, 24]. Direct price elasticity η_p is defined by Equation 5.2 with variables used in Figure 5-3.

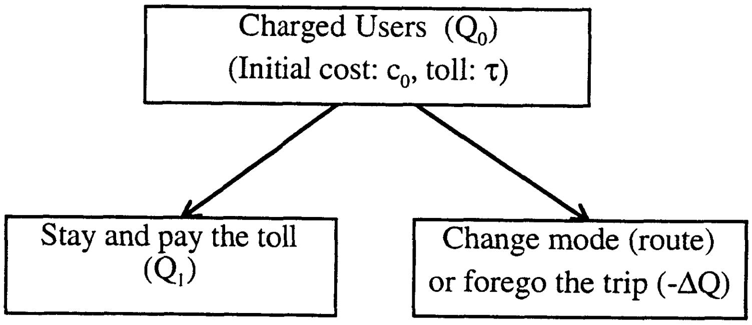

Figure 5-3: Direct price elasticity

$$\begin{aligned} \eta_p &= \frac{\Delta Q/Q}{\Delta P/P} \\ &= \frac{\Delta Q/Q_0}{\tau/c_0} \\ &= \frac{(Q_1 - Q_0)/Q_0}{\tau/c_0} \end{aligned} \tag{5.2}$$

where

ΔQ = change in quantity (number of trips in the case of transportation),

Q = quantity,

ΔP = change in price,

P = price,

Q_0 = number (volume) of charged users,

τ = amount of toll,

c_0 = initial cost of travel,

Q_1 = number (volume) of users who stay on the charged facility.

Direct price elasticity represents the percent change in the amount demanded due to one percent increase in cost. For example, if demand decreases by 0.3% when the cost is increased by 1%, direct elasticity is -0.3.

For direct elasticity of automobile travel, the literature suggests "a range from -0.1 or -0.2 at the low end to -0.3 or -0.4 at the high end, depending on the level of charge, the initial costs of travel, and the capacity of alternative roads and transit systems"[3].

5.3.2 "Avoidance Elasticity" and "Willingness-to-Shift" Modeling

Direct price elasticity varies considerably, depending on the availability of alternatives. The existence of alternatives usually makes elasticity greater. In the case of congestion pricing, users are able to avoid charges not only by changing their mode of travel or giving up their trips, but also by shifting their time of travel to unpriced, off-peak periods. In other words, time-shifting is one of the alternatives that is available for users. Thus, the direct price elasticity around the boundaries of pricing periods is higher in its absolute value (more elastic).

Instead of using different direct price elasticities for each time zone, this thesis employs a constant elasticity for the number of users who consider avoiding tolls. This elasticity is named "avoidance elasticity" to distinguish it from other elasticities. Among those who consider avoiding tolls however, there are some who shift their time of travel to untolled, non-peak periods, depending on their own flexibility, or "willingness-to-shift". Furthermore, among those who cannot shift their time of trip, some will change the mode (or route) or forego their trips entirely. This flow is shown in Figure 5-4.

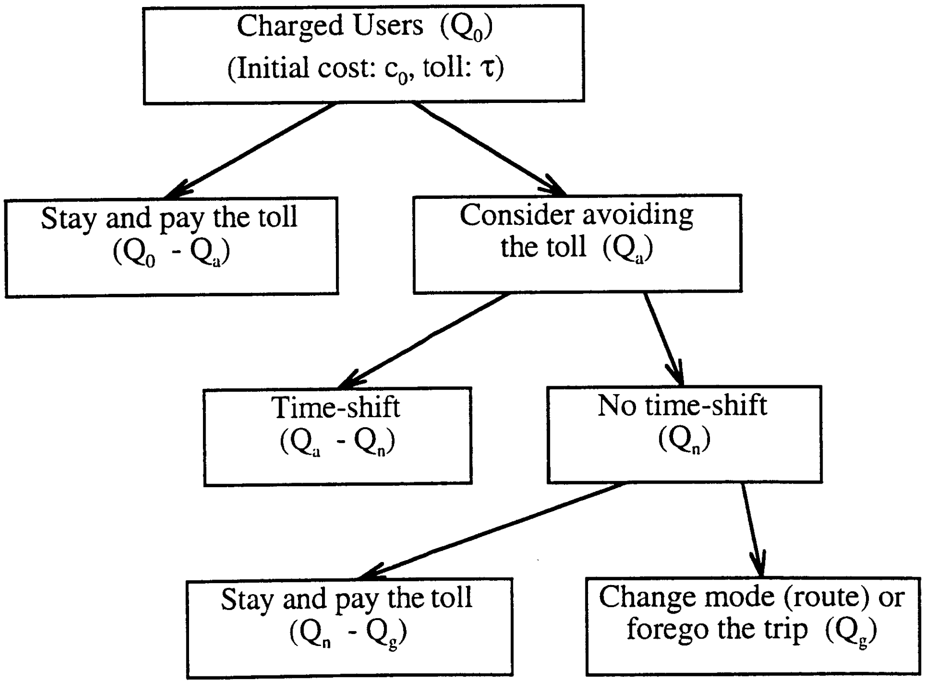

Figure 5-4: "Avoidance elasticity" and "willingness-to-shift" modeling flow

Avoidance Elasticity

The top branch in Figure 5-4, which is replicated in Figure 5-5, indicates the distinction between those who consider avoiding tolls and those who do not care about paying tolls and make no effort to avoid them.

This distinction between the two groups can be more easily understood in the case of transit. Think of commuters who take a subway to work and use monthly passes, and imagine their reactions to an increase in the pass price by, say, 10%. Some commuters may think of changing their mode of travel or stopping the use of passes, while others may not even think of other alternatives. It is not exactly the same in the case of congestion pricing, but we can assume that some portion of users will not even consider avoiding tolls if they are low enough.

The ratio between those two groups should depend on the magnitude of the toll being applied and can be measured as a form of elasticity. This elasticity is called "avoidance elasticity" (η_a) in this thesis and defined in Equation 5.3.

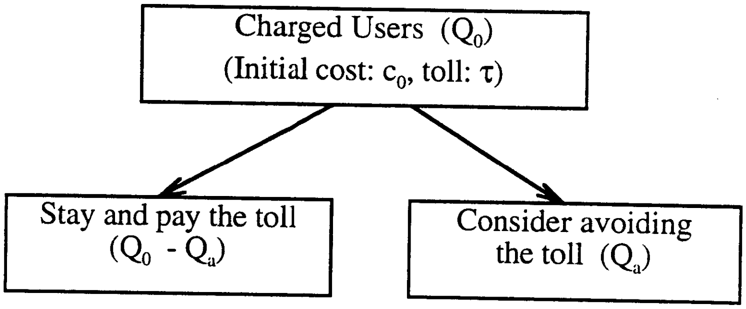

Figure 5-5: Avoidance elasticity

$$\begin{aligned}\eta_a &= \frac{Q_a/Q_0}{\Delta P/P} \\ &= \frac{Q_a/Q_0}{\tau/c_0} \qquad (5.3)\end{aligned}$$

where

Q_0 = number (volume) of charged users,
Q_a = number (volume) of users who consider avoiding the toll,
ΔP = change in price,
P = price,
τ = amount of toll,
c_0 = initial cost of travel.

Unlike direct price elasticity (η_p), avoidance elasticity (η_a) does not vary with the availability of a time-shifting option. Think of road users having to pay congestion pricing tolls unless they change time or mode/route. If they habitually travel through the charged facility at 8:32 a.m. and the pricing starts at 8:30 a.m., they are more likely to shift their time of travel to an unpriced period than are those who travel at 9:00 a.m. because the latter have to shift their time more radically than the former. So, in terms of direct price elasticity for the two time periods, the elasticity is greater for the 8:32 a.m. period than it is for the 9:00 a.m. period. However, in terms of avoidance elasticity, as those who do not consider avoiding the toll do not even consider the availability of time-shifting, they travel when they want to and the tolls just accompany their trips. Therefore, avoidance elasticity is assumed to be constant throughout the time.

"Willingness-to-Shift" Function

The second branch in Figure 5-4, which is replicated in Figure 5-6, refers to all those who consider avoiding tolls and indicates the distinction between those who are able to shift time of travel and those who are not among those who consider avoiding the toll.

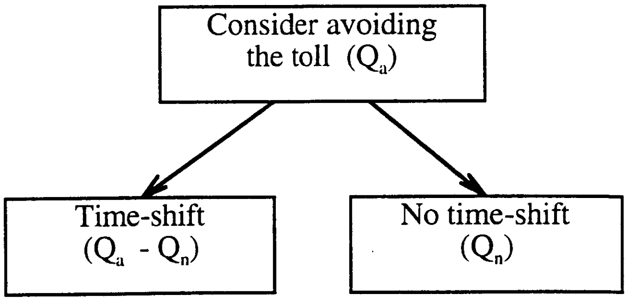

Figure 5-6: Time-shifting of those who consider avoiding the toll

In this thesis, it is assumed that the number of users who shift their time of travel from a priced time zone to an unpriced time zone depends on (1) the time difference between the priced time zone and the unpriced time zone, and (2) characteristics of users' time flexibility. Then, on the basis of these assumptions, the users' time flexibility was formulated as a "willingness-to-shift" function, which measures users' willingness to adapt their time of travel.

First, the probability density function for the amount of time that users are able to shift is assumed to be distributed exponentially with a single parameter β, which represents the mean or the expected value of the amount of time that users are able to shift. This function is defined in Equation 5.4, and its shape is shown in Figure 5-7.

$$f(t) = \frac{1}{\beta} e^{\left(-\frac{t}{\beta}\right)} \tag{5.4}$$

where t is time and β is a parameter.

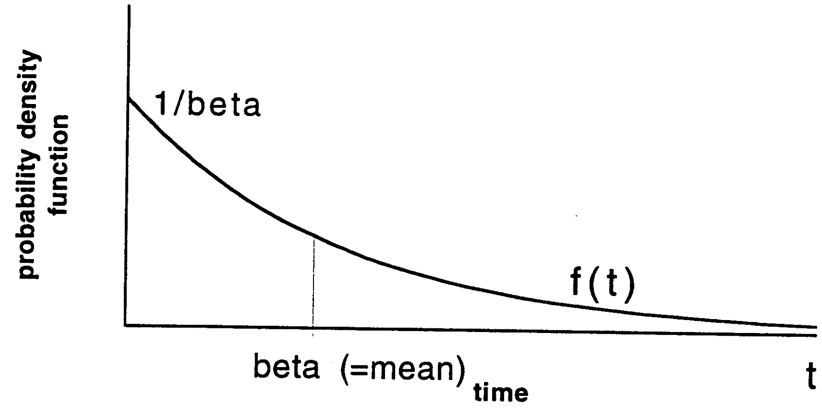

Figure 5-7: Probability density function for the amount of time-shifting

An integration of the probability density function will provide the cumulative density function (Equation 5.5 and Figure 5-8).

$$F(t) = 1 - e^{\left(-\frac{t}{\beta}\right)} \tag{5.5}$$

The total number of people who consider avoiding tolls (Q_a) multiplied by the cumulative density function (Equation 5.5) will provide the willingness-to-shift function $Q_{wts}(t)$. This is written as Equation 5.6, and its shape is shown in Figure 5-9

$$Q_{wts}(t) = Q_a \cdot \left(1 - e^{\left(-\frac{t}{\beta}\right)}\right) \tag{5.6}$$

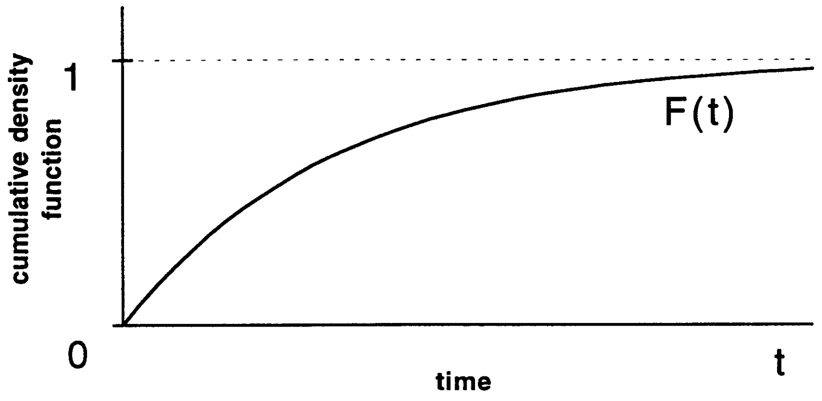

Figure 5-8: Cumulative density function for the amount of time-shifting

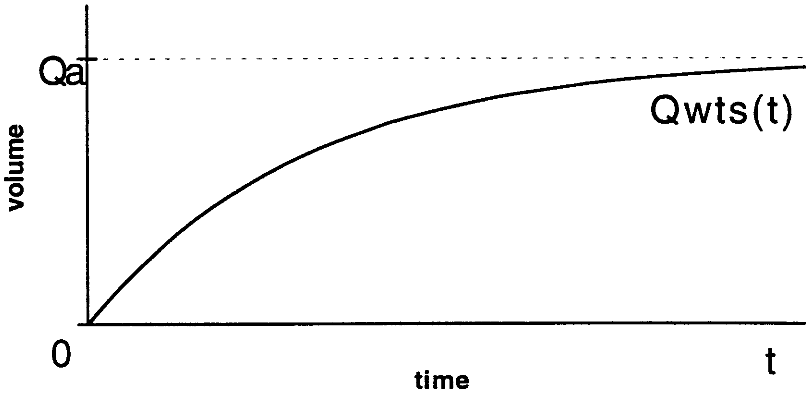

Figure 5-9: Willingness-to-shift function

Time-Shifting Simulation

The willingness-to-shift function derived as Equation 5.6 and Figure 5-9 can be used to simulate time-shifting of users. Suppose simulating the time-shifting of users from a time zone $T_0 < T < T_0 + \Delta T$ to another time zone $T_2 < T < T_2 + \Delta T$ and the pricing starts at time T_1 ($T_2 < T_1 < T_0$, or $T_0 < T_1 < T_2$ for the other end of pricing period)[8] as is drawn in Figure 5-10.

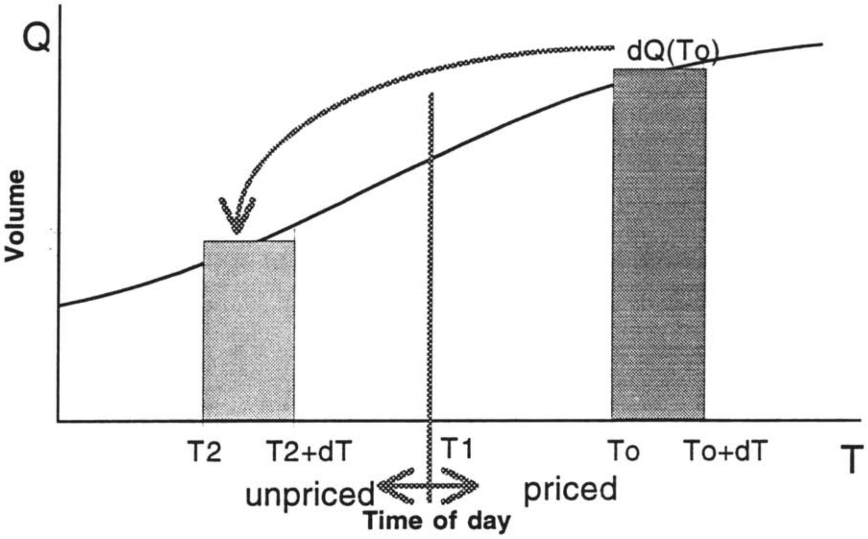

Figure 5-10: Time-shifting simulation (time of day–volume)

The total number of users considering to avoid the toll $Q_a(T_0)$ can be calculated using Equation 5.3. Then, the willingness-to-shift function is expressed as Equation 5.7 and has the shape of Figure 5-11.

$$Q_{wts}(t) = Q_a(T_0) \cdot \left(1 - e^{\left(-\frac{t}{\beta}\right)}\right) \tag{5.7}$$

Since users in time zone T_0 have to shift their time of travel more than $T_0 - T_1$ in order to avoid the toll, those whose time is not flexible enough cannot shift their time of travel. Those users are represented as the "no-shift" part along the vertical axis in Figure 5-11, and the number is $Q_{wts}(T_0 - T_1)$. The number of users shifting from time zone T_0 to time zone T_2 is represented as the "shift to T_2" part in Figure 5-11 and the mathematical representation is:

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[8] To avoid confusion, capital T is used for time of day, and lowercase t is used for time length in this thesis.

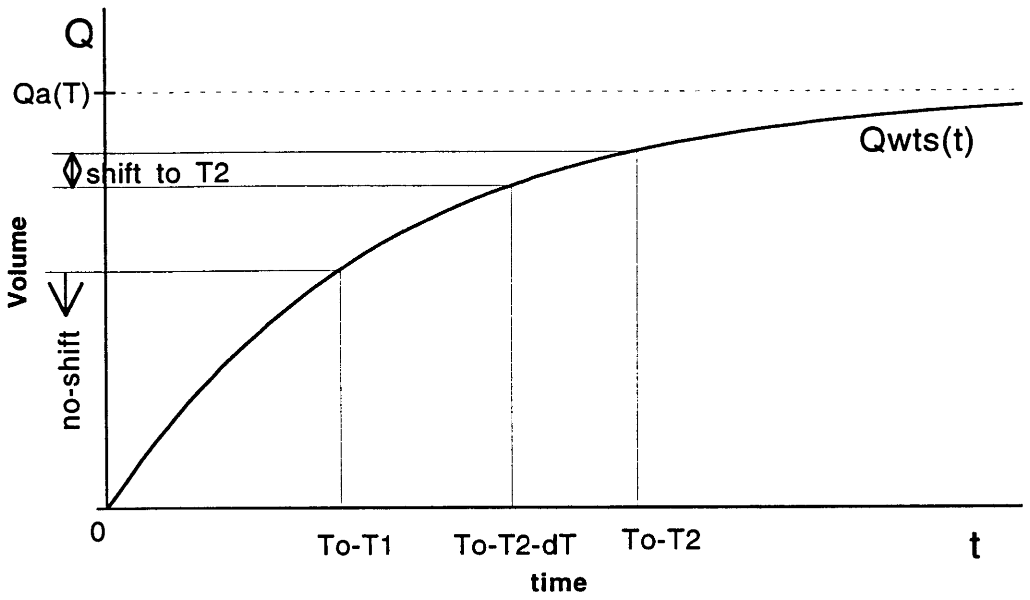

Figure 5-11: Time-shifting simulation (willingness-to-shift)

$$\begin{aligned} Q_s &= Q_{wts}(T_0 - T_2) - Q_{wts}(T_0 - T_2 + \Delta T) \\ &= Q_a(T_0) \cdot e^{\left(-\frac{T_0 - T_2}{\beta}\right)} \cdot \left(1 - e^{\left(-\frac{\Delta T}{\beta}\right)}\right) \end{aligned} \tag{5.8}$$

Users Unable to Shift Time of Travel

Finally, the bottom branch in Figure 5-4, which is replicated in Figure 5-12, indicates the path of those who consider avoiding the toll but unable to shift their time of travel due to their inflexibility in time. Some are assumed to change mode or forego their trips, and the others are assumed to accept the toll and stay on the facility although they tried to avoid it[9]. In this thesis, the ratio of the two groups of users are assumed to be constant with a rate r_g defined as[10]:

$$Q_g = Q_n \cdot r_g \tag{5.9}$$

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[9] Those users end up the same choice as those who chose to stay on the facility without considering to avoid the toll at the top branch of Figure 5-4, and seem to have the same utility characteristic in the sense they get the greatest utility on this mode at the time they travel. However, by dividing those users into two segments, it became possible to use a constant "avoidance" elasticity regardless of the time of day. If these two segments are combined and direct price elasticity is used, the elasticity should vary depending on the time of day.

[10] This ratio is assumed to be independent from the magnitude of price (τ/c_0) since it is already taken into account in Q_g.

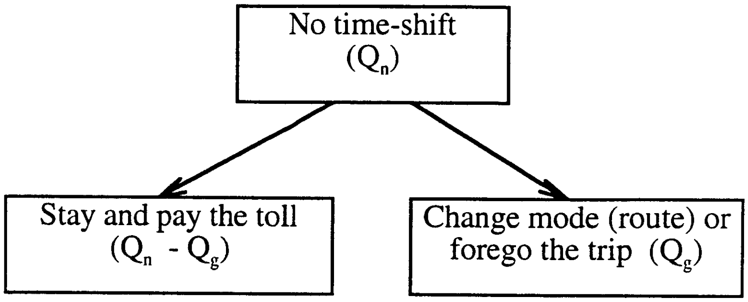

Figure 5-12: Mode (or route) change of users unable to shift time

Relationship between Direct Price Elasticity (η_p) and Avoidance Elasticity (η_a)

The direct price elasticity is widely used and its values are estimated for various cases. However, the avoidance elasticity is a new concept and no estimates or survey results are available. Also, the ratio of volumes between those who leave the facility against those who cannot shift their travel time (r_g) is not an available value.

However, by taking the extreme case in which the toll is applied for the whole day instead of only for peak periods, a relationship among those variables can be obtained. In this limit case, time-shifting is not an option for users and those who consider avoiding tolls can only have an option to change their mode of travel (or route) or forego their trips entirely ($Q_a \to Q_n$). Then the number of users who leave the facility is given as follows:

$$Q_g \to -Q_0 \cdot \eta_a \cdot \frac{\tau}{c_0} \cdot r_g \tag{5.10}$$

Q_g in Equation 5.10 should be equal to the value calculated from the direct price elasticity formula (Equation 5.2) since this limit case is equivalent to ordinary tolls in which uniform tolls are charged all through the day. Therefore, from Equations 5.2 and 5.10, the relationship between avoidance elasticity η_a and direct price elasticity η_p is obtained as follows:

$$\begin{aligned} Q_g = -Q_0 \cdot \eta_a \cdot \frac{\tau}{c_0} \cdot r_g &= -Q_0 \cdot \eta_p \cdot \frac{\tau}{c_0} \\ \eta_a \cdot r_g &= \eta_p \end{aligned} \tag{5.11}$$

5.4 Simulation Results and Analyses

Using the model described in Section 5.3, a series of simulations have been run. The base case is based on the base conditions described in Section 5.2, and the emission characteristics of the base case will be presented in Section 5.4.1. Then the policies introduced in Section 5.2 have been applied to see the emission impacts of those policies. Those emission impacts will be presented in two forms. First, emission impacts of each policy with various magnitudes will be presented in Section 5.4.2. Secondly, "iso-impact" lines of emission reductions will be presented in in Section 5.4.3. The idea of "iso-impact" lines comes from iso-quant lines in production functions. Iso-quant lines represent combinations of inputs which produce the same amount of product. An "iso-impact" line used in this thesis represents policy magnitudes across various policies which generate the same amount of impacts, or emission reductions.

5.4.1 Base Case Emissions

The base case emissions are calculated on the basis of input data and assumptions described in Section 5.2. Figure 5-13 shows HC emissions measured by grams per mile of highway (per lane). Emissions are broken down by vehicle types and age. Although vehicle composition is assumed to stay the same regardless of the time of day in the base case, emission shares of each vehicle type varies by time. This is because different vehicles have different reactions to the changes in travel speed. The time on the horizontal axis indicates the time at the end of each 15-minute time zone (6:30 is for the time zone from 6:15 a.m. to 6:30 a.m.).

Figures 5-14 and 5-15 are for the CO and NO_x emissions, respectively. Variation in contributions of the three vehicle types (LDGV, LDGT, and HDDV) are similar in the HC and CO emissions, but in the NO_x emissions, contributions of HDDV are substantially larger than they are in the HC and CO emissions. Therefore, emission reduction policies that mainly targets emissions from HDDV are more effective to reduce the overall NO_x emissions.

5.4.2 Emission Reductions of Each Policy

Ordinary Congestion Pricing

Under this policy, the users within the peak period of 7:00 a.m. to 8:30 a.m. are charged for the tolls of $0.10, $0.15, and $0.20 per VMT while the users outside of the peak period are not charged with any toll.

Reaction to those tolls are formulated with the model described in Section 5.3 as an increase in travel cost. Direct price elasticity (η_p) is set to be -0.16 as reported in Chan and Ou (1978) as a value

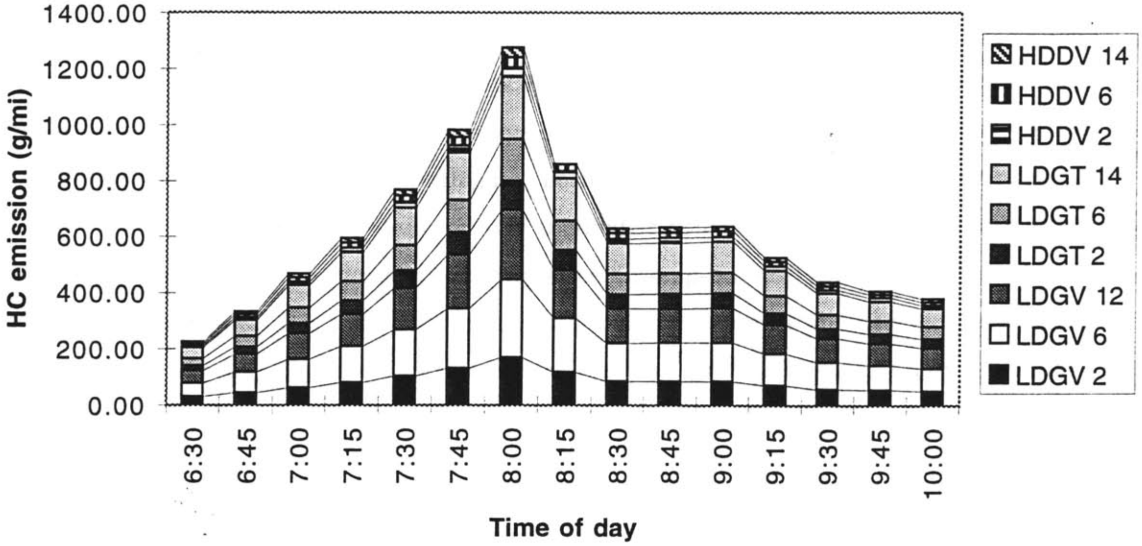

Figure 5-13: *HC* emissions for the base case

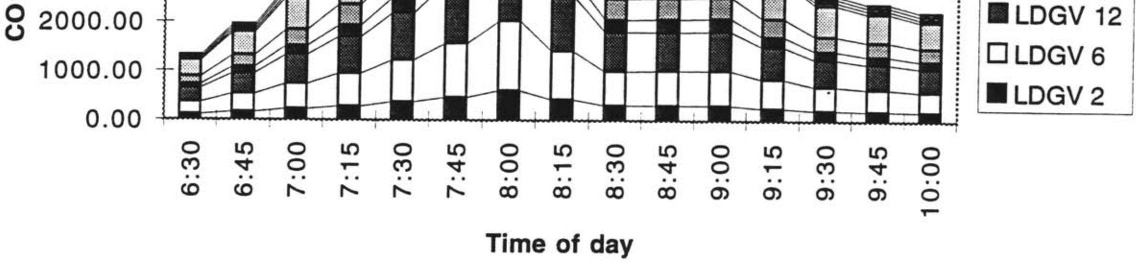

Figure 5-14: *CO* emissions for the base case

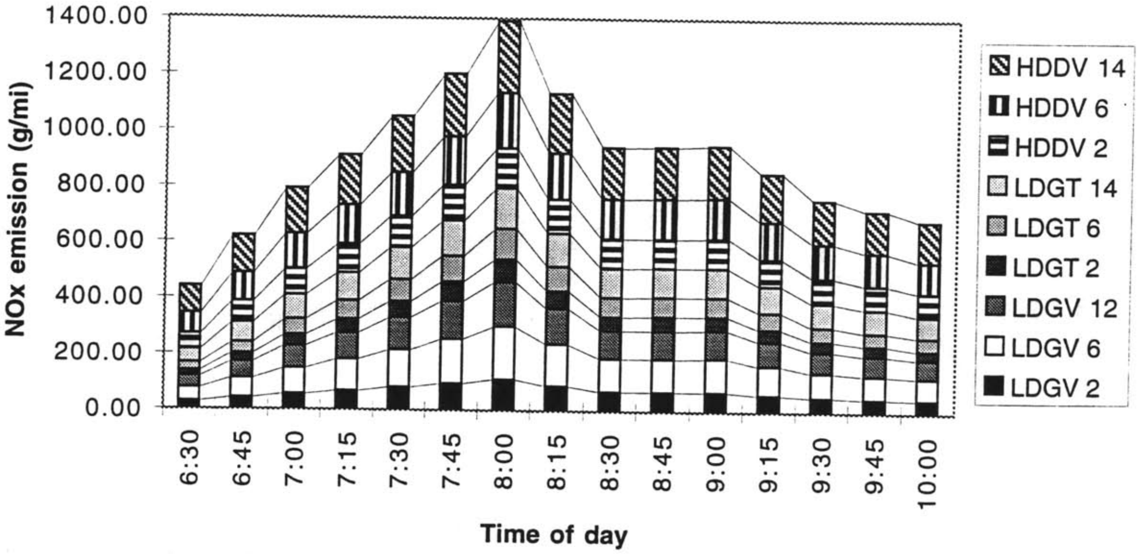

Figure 5-15: NO_x emissions for the base case

for the Washington D.C. area[7]. Avoidance elasticity (η_a) is assumed to be 0.30, and therefore, the constant rate for the share of users who change mode or forego the trip (r_g)[11] becomes 0.533. The parameter (β) for the willingness-to-shift function is assumed to be 20 minutes. These elasticities and the parameter are set to be equal for all vehicle types, but they could also be set differently across different vehicle types to reflect differences in socio-economic characteristics of each vehicle types.

Figure 5-16 shows the traffic volume for the base case and the three toll level cases. Traffic volume in time periods of 7:00 (6:45 a.m. to 7:00 a.m.) and 8:45 (8:30 a.m. to 8:45 a.m.) in the figure show peaks in addition to the original peak at 8:00 (7:45 a.m. to 8:00 a.m.). These peaks occur right before and after the charged period (sometimes called "shoulders") and are also seen in Figure 2-7, which shows variations in traffic volumes in the case of Singapore's Area Licensing Scheme (ALS). It is one of the advantages of the "avoidance elasticity" and "willingness-to-shift" modeling that this peaking characteristics can be simulated.

Figure 5-17 shows the travel speed for the base and the three toll level cases, which is calculated from the traffic volume using the volume-speed relationship (Equation 5.1).

Traffic volume (Figure 5-16) and travel speed (Figure 5-17) are used to calculate emissions for the three toll level cases. The results are presented in Figure 5-18 as a radar chart. The four axes denote the percentage reductions of emissions of three pollutants—hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x)—and the vehicle miles traveled (VMT) from the base

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[11] It is defined in Equation 5.9.

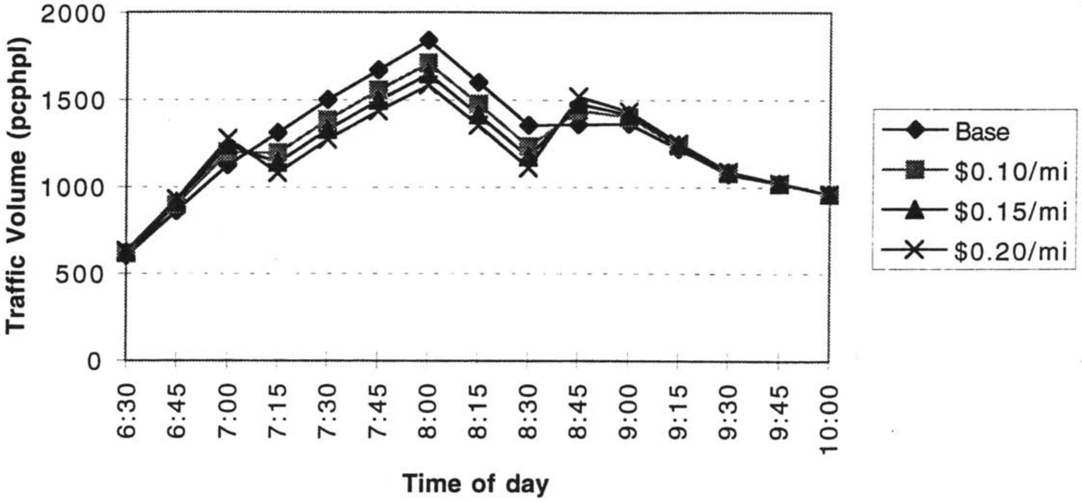

Figure 5-16: Traffic volume before and after ordinary congestion pricing

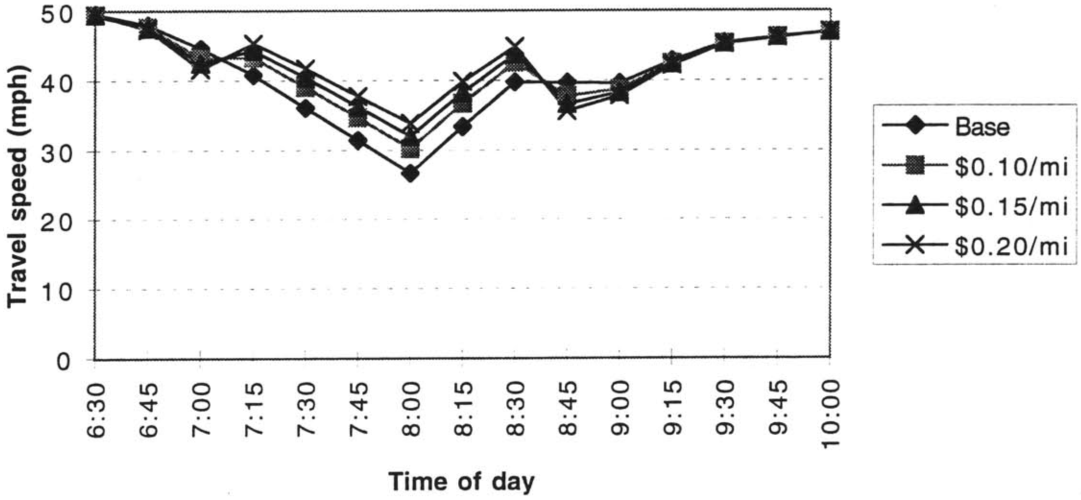

Figure 5-17: Travel speed before and after ordinary congestion pricing

case. The three lines denote three toll levels ($/mile) as noted in the caption box. For example, an application of $0.15/mile toll would reduce the HC, CO, and NO_x emissions by 9.4%, 9.5%, and 4.5%, respectively, and VMT by 3.6%.

These reductions in emissions and VMT do not mean overall reductions in the area or the road system if the pricing is applied to a point of a road or to a single facility (a point of a highway, bridge, tunnel, etc.). In this case, users shifted to alternative routes to avoid the charges would cause more emissions and VMT in other locations, and the calculated reductions are limited to the priced facility. However, if the pricing has a form of zone pricing, charges for distance traveled, or congestion-specific charges, these calculated reductions can be interpreted as the ones for the whole area.

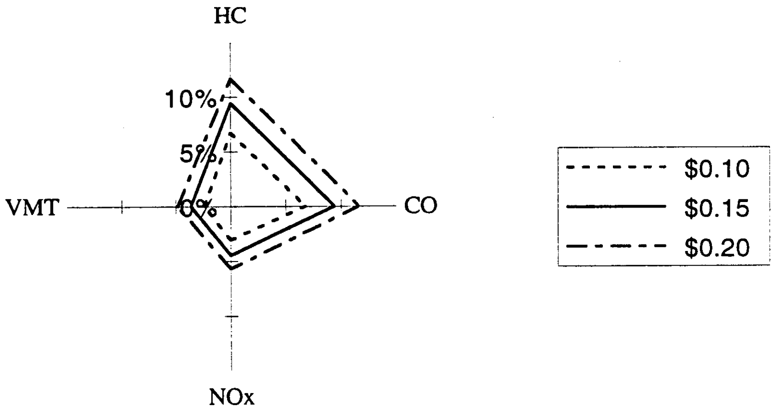

Figure 5-18: Emission reductions under ordinary congestion pricing

Pollution-adjusted-rate Congestion Pricing

Different toll levels and priced periods are applied for each vehicle (and age) type in this policy. As it was for the ordinary congestion pricing, users are charged only during peak periods, and users of non-peak periods are free of charge. In the simulations, the ratio of tolls among the nine vehicle-type groups and the time periods in which pricing is applied are fixed as shown in Table 5.2, in which the ratios are given relative to LDGV2 (light-duty gasoline-powered vehicles, 2 years of age). For example, the ratio of 150% for LDGT6 (light-duty gasoline-powered trucks, 6 years of age) means the toll for LDGT6 is 1.5 times higher than the toll for LDGT2, and it is applied for the time period of 7:00 a.m. to 8:30 a.m. instead of the time period of 7:30 a.m. to 8:15 a.m. for LDGT2.

Emission levels are calculated for the average toll[12] of $0.10, $0.15, and $0.20 per VMT.

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[12] The average toll is defined as the total revenue divided by the total number of vehicles paying tolls.

vehicle type	2 year old	6 year old	12 year old	14 year old
LDGV	100% 7:30–8:15	110% 7:30–8:15	120% 7:00–8:30	
LDGT	130% 7:00–8:30	150% 7:00–8:30		400% 6:45–8:45
HDDV	300% 6:45–8:45	350% 6:45–8:45		400% 6:45–8:45

Table 5.2: Toll levels and priced periods

Figure 5-19 shows the traffic volume for the base case and the three toll level cases. The peaking characteristics for shoulders are not as clear as in the case of ordinary congestion pricing (page 97). This is because different pricing periods are applied to each vehicle group in this pricing scheme. This characteristics of pollution-adjusted-rate congestion pricing gives an advantage for emission reductions as the high volume at the shoulder periods sometimes cause additional emissions.

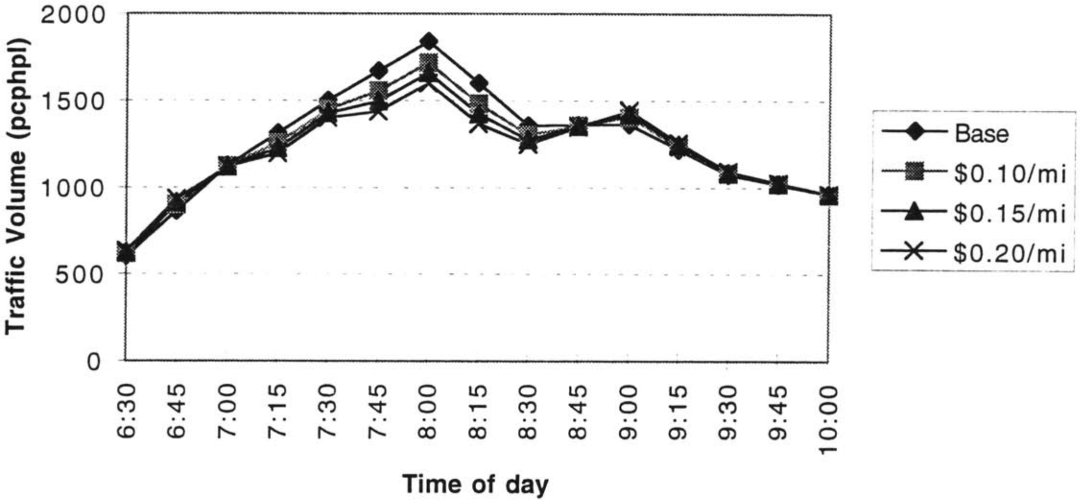

Figure 5-19: Traffic volume before and after pollution-adjusted-rate congestion pricing

Figure 5-20 shows the travel speed for the base and the three toll level cases, which is calculated from the traffic volume using the volume-speed relationship (Equation 5.1).

Traffic volume (Figure 5-19) and travel speed (Figure 5-20) are used to calculate emissions for the three toll level cases. The results are presented in Figure 5-21 as a radar chart. It can be read in the same manner as described for the case of ordinary congestion pricing (page 99). For example, an application of \$0.15/mile average toll would reduce the HC, CO, and NO_x emissions by 10.0%, 10.8%, and 7.8%, respectively, and VMT by 3.2%.

If you compare this result (Figure 5-21) with the one for the case of ordinary congestion pricing

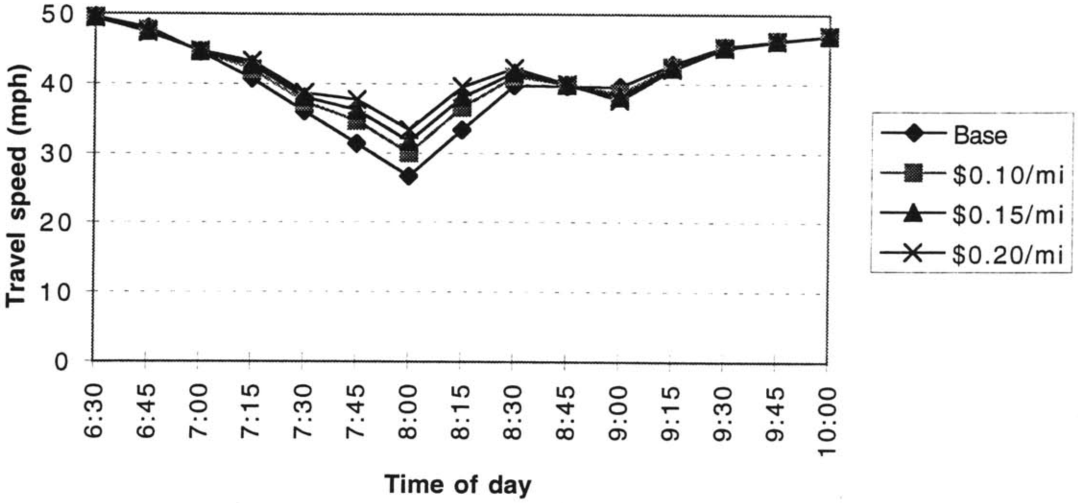

Figure 5-20: Travel speed before and after pollution-adjusted-rate congestion pricing

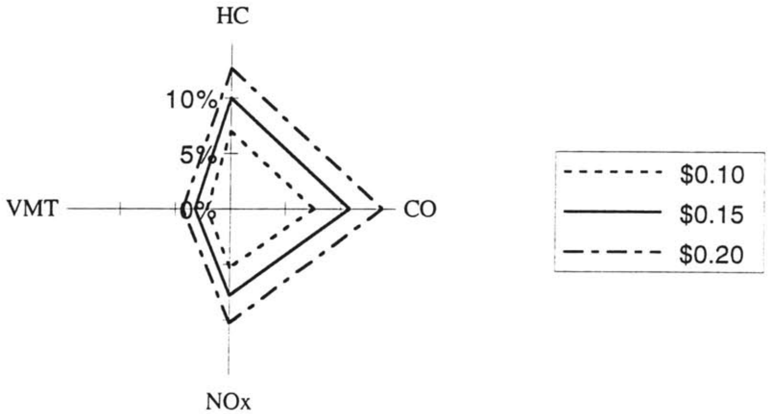

Figure 5-21: Emission reductions under pollution-adjusted-rate congestion pricing

(Figure 5-18), you can see the emission reductions of the pollution-adjusted-rate congestion pricing are higher and the VMT reductions lower for the same amount of tolls. As pricing periods are different between the two, you cannot simply say the toll levels are comparable even if the average tolls are the same (because the numbers of users charged are different). However, as the amount of VMT reduction indicates the number of users affected (or charged) to a certain degree, low VMT reductions and high emission reductions together indicates the high effects of the pricing scheme on emission reductions with a low impact on users' travel.

In addition, the difference in NO_x reductions between Figure 5-21 and Figure 5-18 are more significant than other pollutants. This is because the HDDVs are charged with greater amounts of tolls than the other two vehicle types (gasoline-powered vehicles). As HDDVs emit much higher levels of NO_x than gasoline-powered vehicles, forcing HDDVs out of congestion reduce NO_x emissions.

Reducing Numbers of Old Vehicles

Reducing numbers of old vehicles, sometimes called as "early retirement" or "klunker" program is simulated as reducing the number of old vehicles (12 year olds for LDGV and 14 year olds for LDGT and HDDV) and replace them with new vehicles (2 year olds for every vehicle type). Therefore, the traffic characteristics such as traffic volume and travel speed are assumed to remain unchanged, but vehicle composition changes, which brings a change in emissions.

Considering the fact that this program takes considerably different efforts depending on the vehicle type (Forcing old automobiles to retire and old trucks to retire must require quite different policy considerations and efforts.), the simulations are conducted on the three vehicle types separately at first. Then, the combined case, in which numbers of old vehicles of all three vehicle types are reduced uniformly by the same amount, is analyzed.

The ratios of numbers of old vehicles to the total number of vehicles are shown in Table 5.3 by vehicle type. These numbers are taken from Table 5.1 and show the ratios for the base case (before the policy application).

vehicle type	LDGV12	LDGT14	HDDV14
ratio to the total number of vehicles	17.47%	8.14%	1.62%

Table 5.3: Vehicle composition of old vehicles

Due to the assumption that the traffic characteristics remain unchanged even after the policy is applied, the percent reduction in old vehicles of each vehicle type has a linear impact on emission reductions. In other words, a 20% reduction in the number of old vehicles has a double impact compared to a 10% reduction. Thus, only the impacts of 10% reduction in old vehicles are presented in Table 5.4 for the cases of each vehicle types and all vehicle types combined, in which numbers of old vehicles of all three vehicle types are reduced by 10%.

vehicle type	LDGV12	LDGT14	HDDV14	all combined
HC reduction	-0.75%	-1.13%	-0.04%	-1.92%
CO reduction	-1.42%	-1.98%	-0.09%	-3.49%
NO_x reduction	-0.40%	-0.70%	-1.13%	-2.23%

Table 5.4: Emission reductions under reducing old vehicles by 10%

A graphical presentation of emission and VMT reductions is given in Figure 5-22 for the case of all vehicle types combined.

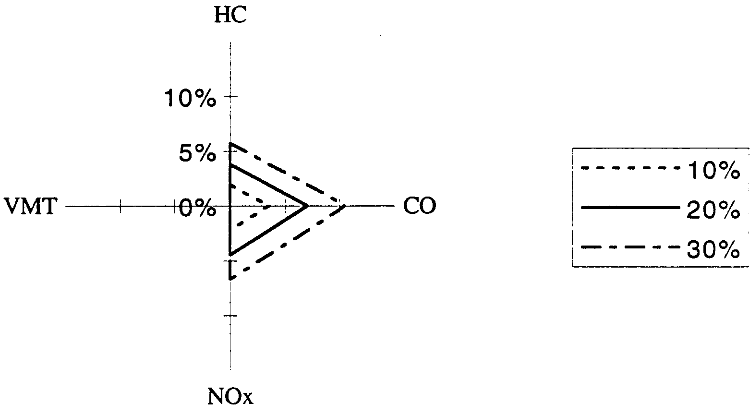

Figure 5-22: Emission reductions under early retirement policy

Because of the assumption that reduced old vehicles are replaced by the same number of new vehicles, VMT does not change after the application of this policy as you can see from Figure 5-22. Figure 5-22 also shows that this policy is effective to reducing the CO emissions. This is because CO emissions increase in greater amount as vehicles become old. If you compare the base case emissions of the three pollutants (Figures 5-13 through 5-15), you can see that the emission shares of the old vehicles (LDGV2, LDGT14, and HDDV14) are relatively higher in CO emissions (Figure 5-14) than in the other two.

Demand Reduction

Demand reduction simulates situations, such as public transportation improvement, license plate restriction, and ride-share promotion, in which the overall vehicle volume decreases. This is simulated as uniform volume reduction in each time zone as is shown in Figure 5-23.

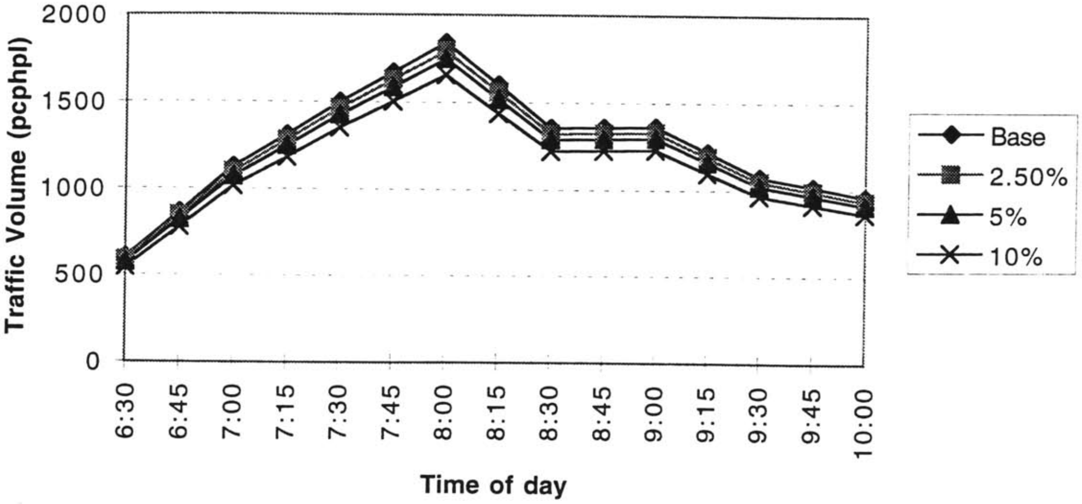

Figure 5-23: Traffic volume before and after demand reduction policy

Figure 5-24 shows the corresponding travel speed for the base case and three demand-reduction levels of 2.5%, 5%, and 10%. Travel speed increases as traffic volume decreases, but the amount of increase is greater if the initial volume is high (more congested condition). Therefore, the speed increase around the peak period (8:00 in Figure 5-24) is greater than other time periods. A conceptual illustration of this relationship is given in Figure 2-1-c and the exact mathematical expression used in this simulation is given as Equation 5.1.

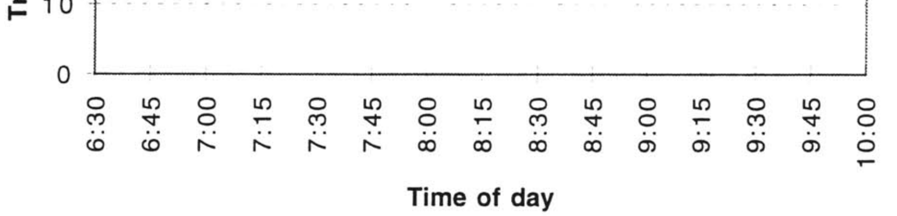

Figure 5-24: Travel speed before and after demand reduction policy

Figure 5-25 shows emission impacts under this policy with demand reductions of 2.5%, 5%, and

10%.

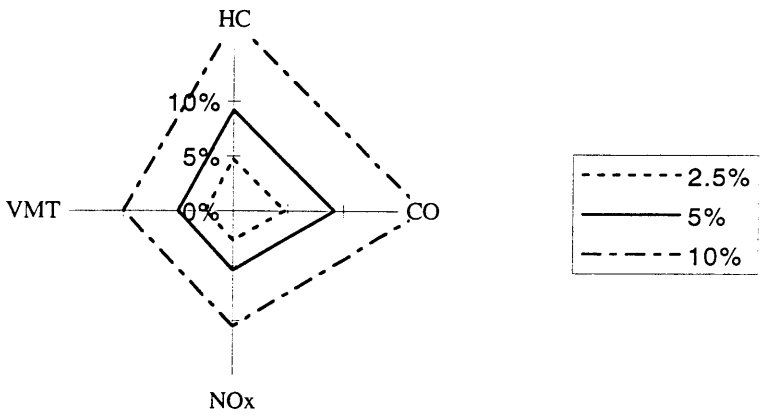

Figure 5-25: Emission reductions under demand reduction policy

If you compare this result with the one for the early retirement program (Figure 5-22), you can see that even a 5% reduction in demand has a comparable impact with 30% reduction of old vehicles, which is equivalent to 8.2% (= 27.2% x 30%) of total vehicles since 27.2% of total vehicles are assumed to be old vehicles (Table 5.3). This difference in impact between the two policies comes from the difference in the assumptions that the total VMT remains unchanged in the early retirement policy while the demand reduction decreases the total VMT and increases travel speed.

In this simulation, the demand is assumed to decrease uniformly by 2.5%, 5%, or 10%. In general however, reducing the demand for peak periods is more difficult than reducing the demand for non-peak periods, and a uniform reduction regardless the time of day like in this simulation is often quite difficult in practice. In the case of pricing for example, direct price elasticities for peak periods is generally higher than those for non-peak periods, which means reducing the demand for non-peak periods by pricing is easier than reducing the demand for peak periods. Therefore, a uniform reduction in demand as is simulated here is rare in practice, but some cases such as an opening of a new public transit or economic depression in the area may cause uniform decline in demand.

Introduction of Zero-emission Vehicles (ZEVs)

Introduction of ZEVs is simulated in such a way that a certain portion of each vehicle type (automobile, light-truck, and heavy-truck) is replaced with ZEVs. As ZEVs emit no emission and indirect emissions (from producing the electricity, for example) are not included in the simulation, replacing existing vehicles with ZEVs is similar to excluding some emissions from the calculation. Therefore, uniform reductions in all vehicle types resulted in emission reductions by the same percentage as the portion of ZEVs. For example, introduction of ZEVs by 5% resulted in the emission reductions of 5% for all three pollutants. The simulation results are graphically represented in Figure 5-26 for the ZEV introductions by 2.5%, 5%, and 10%.

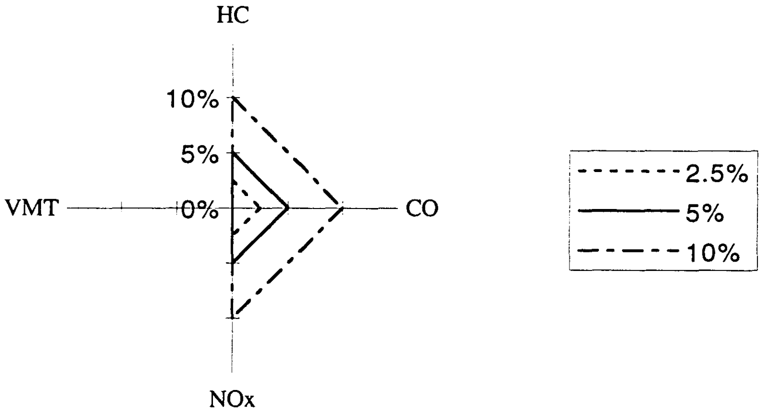

Figure 5-26: Emission reductions under ZEV introduction

From Figure 5-26, you can see that VMT does not change under this policy. This is because traffic characteristics (volume and speed) are assumed to remain unchanged with the introduction of ZEV. In other words, even after some ZEVs are introduced, people are assumed to take the same trips (with different vehicles for some people).

Another assumption is made on the use of ZEVs. The share of ZEVs are assumed to be the same for all time periods. It may not be a reasonable assumption in some cases as ZEVs are more likely to be owned by public sectors and not used for commuting but for public services. In this case, the share of ZEVs during peak periods may be lower.

5.4.3 "Iso-impact" Lines of Emission Reductions

In the previous section, air pollution impact of various policies has been presented. As you can see, the same level of emission reductions can be achieved by various policies with different degrees of efforts. For example, it turned out that congestion pricing of $0.30/mile for the morning peak-period of 7:00 a.m. to 8:30 a.m. resulted in 15% reduction in hydrocarbon emissions. This level of 15% reduction in HC emissions can also be achieved by demand reduction of 8.5%.

In order to illustrate those equivalent emission levels across the policies, "iso-impact" lines—the lines with the same emission reduction levels—will be introduced in this section. Iso-impact lines will be derived for each of the three pollutants (HC, CO, and NO_x) and presented.

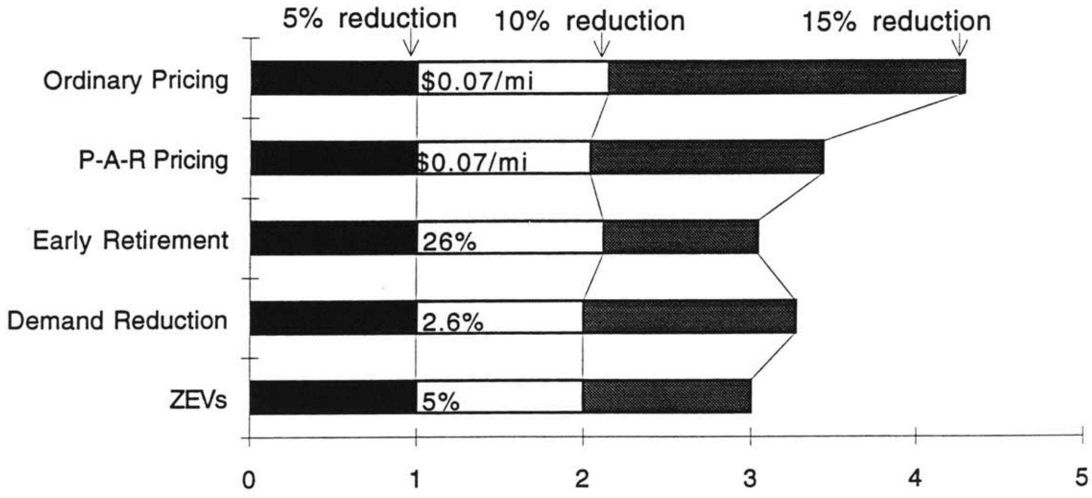

Figure 5-27: Iso-impact lines for HC emission reductions

Figure 5-27 shows the iso-impact lines for the HC emissions. The length of bars are normalized by the values (amount of toll for pricing policies and percentages for other policies) for 5% emission reductions, and the actual values for 5% emission reductions are written on the figure. The numbers on the horizontal axis indicates the values relative to 5% reduction of the policy. For example, you read the value for 10% reduction in ordinary pricing policy is 2.3, which means it requires 2.3 times as large a toll to reduce emissions by 10% as to reduce emissions by 5%. You also read the toll level for 5% reduction is $0.07/mi. Therefore, the toll level of $0.16/mi (= $\$0.07/mi \times 2.3$) is necessary to reduce the emission by 10%.

Figures 5-28 and 5-29 are for CO and NO_x emissions, respectively.

From Figures 5-27 through 5-29, you can see that congestion pricing, especially ordinary congestion pricing, has decreasing marginal impact. In other words, the emission reduction effects of congestion pricing gained from an increase in the amount of tolls becomes smaller if the fare level is high. For example, if you see Figure 5-27, you see the toll level of $0.07/mile reduces the CO emissions by 5%. In order to gain an additional 5% reduction however, the toll must be increased 2.3 times or increase by 130%. Furthermore, in order to achieve yet another 5% reduction (15% in total), the toll must be increased 4.3 times or increase by another 200%. This characteristic is less obvious in pollution-adjusted-rate congestion pricing.

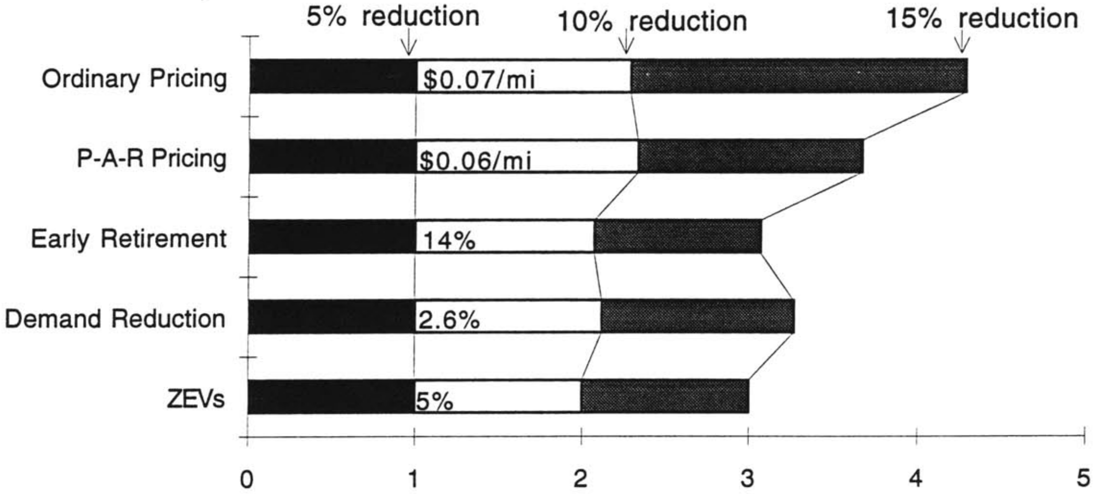

Figure 5-28: Iso-impact lines for CO emission reductions

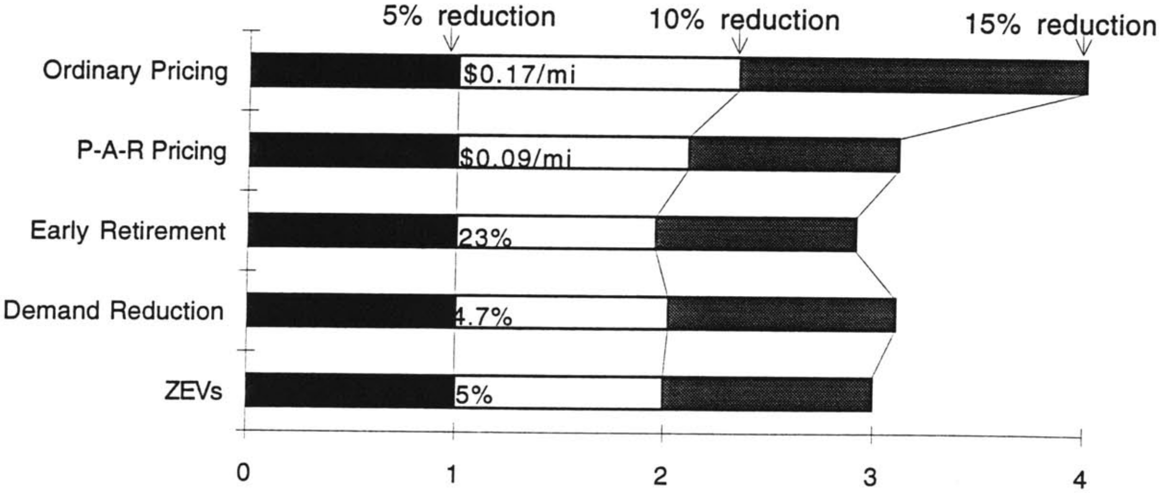

Figure 5-29: Iso-impact lines for NO_x emission reductions

5.5 Limitations of the Results

The simulation results showed the positive effects of congestion pricing policies on air pollution reductions. However, one must be careful interpreting these results. The effects can be smaller or even negative under some conditions or assumptions.

The free flow speed, which is set at 50 mph (=80 km/hour), is one of the factors that affects the simulation results. In high speed ranges, emission levels of some pollutants rise as travel speed increases. This is particularly true for NO_x emissions, as described in Section 3.4 and shown graphically in Figure 3-5. In such cases, emission levels are likely to rise if travel speed is increased by congestion pricing policies. Thus, to minimize these adverse effects, amounts of tolls must be adjusted in the case of pollution-adjusted-rate pricing.

Another factor related to travel speed that may change the simulation results substantially is the existence of hyper congestion. The speed-volume relationship used in the simulations (Equation 5.1) does not represent an unstable flow range, or what is sometimes called hyper congestion[13]. An examination of the general shape of speed-volume curve (Figure 2-1-c) indicates two speeds corresponding to any given volume with the exception of the maximum volume (V_{max}). The lower part of the speed-volume curve represents hyper congestion, but Equation 5.1 represents only the upper part (stable flow). Therefore, the state of hyper congestion is not simulated in the model used in this thesis. Since emissions are substantially higher under hyper congestion due to extremely slow travel speeds, a more dramatic reduction in emissions would have been demonstrated if hyper congestion could have been included in the formulation of the simulation.

The above factors are related to uncertainty in traffic speed. However, even if traffic speed were given or measured perfectly, there would still exist uncertainty in the relationship between traffic speed and emission levels. The speed correction factor used in the formulation (SCF), is known to have wide confidence intervals. Details concerning the uncertainty of SCF can be found in Guensler and Sperling (1994)[25] and Guensler, et al. (1993)[26].

5.6 Summary

In this chapter, the air pollution impact of various policies, including congestion pricing policies, has been simulated. Users' decisions about shifting their time of travel (time-shifting) were modeled with a constant elasticity ("avoidance elasticity") and a function that represents users' time flexibility ("willingness-to-shift function"). Although the avoidance elasticity and willingness-to-shift function

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[13] It corresponds to the level of service (LOS) F in Highway Capacity Manual[56].

were set to be equal for all vehicle types, they could also be set differently across different vehicle types to reflect contrasts in the characteristics of owners of those vehicles.

The simulation results showed that congestion pricing policies reduce emissions in all three pollutants calculated in the simulations (HC, CO, and NO_x). Pollution-adjusted-rate congestion pricing, which this thesis proposes as an air pollution reduction tool, showed greater emission reduction effects than did ordinary congestion pricing, and yet it did not affect travel (VMT) greatly.

In order to compare the emission reduction effects of congestion pricing policies with other policies, equivalent amounts of effort (level of toll, shares of old vehicles replaced in the case of "early retirement program", percentage in reduction of demand, or shares of ZEVs introduced) across various policies were presented as iso-impact lines. They could provide more practical information if the author could have been able to study the levels of practical difficulties required to reach those points in the iso-impact lines. For example, although it is clear from the simulations in Chapter 5 that an ordinary congestion pricing policy with the toll level of \$0.07/mile would provide the same HC emission reduction as a demand reduction by 2.6%, it is less clear how much effort would be needed (the amount of budget, for example) or what the level of impact on users would have to be (the number of people shifting their time, mode, or route of their trips, for example) in order to reach those levels.

Although congestion pricing policies showed positive effects on air pollution reductions in the simulations in this chapter, they could be much smaller or even negative in some cases and also under some assumptions. Some of these concerns were explained in Section 5.5.

Chapter 6

Findings and Policy Implications

6.1 Overview

In the previous chapters, the air pollution impact of congestion pricing policies including "pollution-adjusted-rate congestion pricing" has been investigated. Reviews of the theory and current developments of congestion pricing were given in Chapter 2, and the impact of road transportation on air pollution was described in Chapter 3. A pricing scheme called "pollution-adjusted-rate congestion pricing" was proposed in Chapter 4. This policy attempts to reduce not only congestion but also air pollution by determining amounts of congestion pricing tolls on the basis of vehicles' pollution levels. Finally in Chapter 5, a series of simulations were run to evaluate the impact of congestion pricing and other policies on air pollution.

In this final chapter, findings from the previous chapters will be summarized, and policy implications derived from these findings will be discussed. First, Section 6.2 will discuss issues related to the model used in the simulations. The discussions of the simulated policies will be divided into two sections; Section 6.3 will deal with issues cutting across various policies, and Section 6.4 will be devoted to issues related to each congestion pricing policy—ordinary congestion pricing and pollution-adjusted-rate congestion pricing. Finally, Section 6.5 will make some concluding remarks.

6.2 Modeling Issues

Time-shifting, or adjusting the time of travel to avoid tolls, is one of the unique characteristics of users' reactions to congestion pricing and does not occur when ordinary tolls are in use. If a toll is applied not only to peak periods but to any time of day, users will see no point on shifting their time of travel. In the case of congestion pricing, however, some users will try to avoid tolls by shifting their time of travel from peak period to non-peak period. This is especially apparent around the boundaries of peak periods since users can avoid tolls by making a small change in their time of travel.

Direct price elasticity is normally used in simulations of users' reactions to pricing schemes, and the existence of time-shifting could be modeled if different values were set for each time period. Time periods that are close to boundaries of charged periods must have higher elasticity than those in the middle of charged periods. Although values of direct price elasticity in the case of ordinary tolls are widely available from various surveys and computer simulations, they are not directly applicable to the case of congestion pricing because the values must vary depending on the time period.

In order to simulate the time-shift of users under congestion pricing policies without setting various elasticities to each time period, a constant elasticity named "avoidance elasticity" and a probability function named "willingness-to-shift function" were introduced in Chapter 5. In this model, users' reactions to pricing schemes, including time-shifting, can be simulated with only two parameters, which represent value of time and time flexibility of users. These parameters are also assumed to remain constant regardless of the level of toll, the time and duration of charged periods, and time of day.

Unlike disaggregate demand models, which capture individual users' travel decisions, this model cannot incorporate either the socio-economic characteristics of or the value of time for each user, but it is simpler and does not require these detailed data. Therefore, we argue that this model is more suitable for initial stages of the planning process and provides a general sense of the impact that a given congestion pricing policy will have on air pollution if the values of the parameters for the area to be modeled are provided.

6.3 Crosscutting Issues

In an attempt to compare the air pollution effects of congestion pricing policies with other policies, a concept of the "iso-impact" line was introduced. Iso-impact lines were drawn for each of the three pollutants—hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x).

The iso-impact lines by themselves are not sufficient to allow comparison of political or institutional difficulties in achieving a given amount of air pollution reduction with various policies. The iso-impact lines give the relationship between the level of policy imposition and the level of air pollution reduction. It can be seen in the simulations in Chapter 5, for example, that congestion pricing with the toll level of \$0.17/mi will give the same level of NO_x emission reduction as would a demand reduction of 4.7%, but it is not clear which policy is more difficult to implement. Therefore, additional information on the levels of political or institutional difficulties is necessary to compare policy alternatives that achieve the same emission reduction.

Ordinary congestion pricing and pollution-adjusted-rate congestion pricing were compared by their average tolls. As the total number of vehicles being charged were set to be nearly equal, the effects of these two congestion pricing policies were measured as charging the same (total) amount of tolls on different kinds of vehicles. While the former policy applies toll charges uniformly to all vehicle types, the latter charges higher tolls on "dirty" vehicles and lower tolls on "clean" vehicles. Pollution-adjusted-rate pricing showed greater impact on air pollution reduction as expected.

Simulations were run separately on each policy; combined cases, in which more than one policy is applied at the same time, were not simulated. This area of study awaits further work, and some combinations, such as pollution-adjusted-rate congestion pricing and introduction of zero-emission vehicles (ZEV), are expected to be quite effective.

6.4 Findings for Each Congestion Pricing Policy

6.4.1 Ordinary Congestion Pricing

Congestion pricing has been expected to be an effective tool to reduce air pollution, and the simulation results support this expectation. However, several factors contribute to the effectiveness of congestion pricing on air pollution reduction, and depending on these factors, the results could be negative in some cases. Therefore, careful consideration of these factors is necessary to gain the air pollution benefits that should result from congestion pricing policies.

One of the most influential factors is the unrestricted speed (free-flow speed) on the road. If the road permits a fast free-flow speed, reduced congestion may bring more pollution because fast driving vehicles emit high levels of some pollutants.

Operational design of the pricing system is another factor that affects the air pollution impact of congestion pricing. Point pricing or single facility pricing, in which pricing is applied only at a certain point along a highway or on a facility such as a bridge or a tunnel, seems to be less effective if there are alternative routes to avoid tolls. An additional VMT from the diverted users, who may travel a longer distance in order to take a detour, will offset the emission reduction on the priced facility.

Cordon pricing and zone pricing are more effective than point pricing in preventing charged users from taking longer alternative routes. The simulations introduced in Chapter 5 project a situation like those in zone or cordon pricing schemes since they do not consider emissions from alternative routes. However, these simulations are designated for highways, and careful consideration is required if they are to be applied to a cordon or zone pricing scheme in a central business district (CBD) such as the Area Licensing Scheme (ALS) in Singapore[1]. Traffic on highways is considerably different from that in downtown street systems because the latter is often stopped by traffic lights and other obstacles. Therefore, the environmental effects of pricing policies are more complex for cases like zone or cordon pricing in CBD.

Although there are some uncertainties concerning the air pollution impact of congestion pricing, developments in toll collection technologies have certainly provided the opportunity to make a positive impact on the problem. Electronic toll collection (ETC) systems have been well developed, and continuing development efforts are being made in relation to the Intelligent Transportation Systems (ITS). ETC makes it possible to collect tolls without having to stop vehicles. Therefore, the adverse environmental effects resulting from physically collecting tolls from users can be eliminated.

6.4.2 Pollution-Adjusted-Rate Congestion Pricing

This pricing scheme, the author believes, is a new concept and attempts to reduce air pollution more drastically than ordinary congestion pricing policies do; it tailors the amounts of tolls to fit the emission impact of each vehicle.

It is designed to gain further air pollution reductions than can be obtained by ordinary congestion pricing policies, and simulation results show greater effectiveness in air pollution reductions with even small changes to the congestion characteristics. In areas where air pollution is a serious problem, this pricing policy could provide a solution to vehicle emission reductions.

The higher tolls are applied to "dirty" vehicles—mainly old vehicles and trucks—may bring strong opposition on the basis of equity. Since old vehicles are often owned by low-income people, this policy may not be viable if the adverse effects on the poor are seen to be substantial. Also, higher charges on trucks may face hostile reactions from business leaders. In any case, collateral actions, or other policies implemented with the revenues from this policy, are important as a way to mitigate such political opposition.

This policy will be more effective if it is combined with the introduction of zero-emission vehicles (ZEV). As the amount of toll for these "clean" vehicles during peak periods is lower than for "dirty" vehicles, the share of clean vehicles will become higher during congestion. Thus, extremely clean vehicles like ZEV would provide higher potential for this policy. Also, the lower toll for ZEV will give people some incentive to buy these vehicles. Although this combined case was not studied in

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[1] ALS is described in Section 2.4.1.

the simulations, it must be quite effective.

This policy has not been considered, let alone tested in practice, but it will provide an effective tool to reduce the air pollution impact of road transportation systems without modifying ordinary congestion pricing policies too greatly. For this scheme to gain political attention, the environmental problem must be so serious that it overwhelms any concern for the issue of equity. Some cities in developing or newly-developed countries or in some parts of the United States could gain enough environmental benefits to make up for the inconvenience suffered by displaced or charged road users.

6.5 Concluding Remarks

Attention to congestion pricing has been growing in the United States especially since the Congestion Pricing Pilot Program was established under the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991. In addition, the electronic toll collection (ETC) system has been developed supported by the movement of Intelligent Transportation Systems (ITS). A surge in attention to congestion pricing has happened before but did not lead to successful practical applications except for the case of Singapore. It could be just the same this time as before, but some say it is the time that the long-studied policy takes off to practical implementations. If this is the case, "pollution-adjusted-rate congestion pricing" may be considered as a policy alternative some day.

Appendix A

Characteristics of Pollutants

This appendix is based on EPA (1995)[16].

A.1 Carbon Monoxide (CO)

Carbon monoxide is a colorless odorless poisonous gas formed when carbon in fuels is not burned completely. It enters the bloodstream and reduces oxygen delivery to the body's organs and tissues. People with cardiovascular disease are the most sensitive to the exposure, but healthy individuals are also affected at high levels of exposure. It causes visual impairment, reduced work capacity, reduced manual dexterity, poor learning ability, and difficulty in performing complex tasks. The health-based national air quality standard is set by the Environmental Protection Agency (EPA) at 9 parts per million (ppm) (measured over 8 hours).

A.2 Nitrogen Dioxide (NO_2)

Nitrogen dioxide is a suffocating, brownish gas formed when fuels are burned at high temperatures. It irritates the lungs and lowers resistance to respiratory infections such as influenza. It also has other environmental effects like acid rain and eutophication in coastal and inland waters. The health-based national air quality standard set by the EPA is 0.053 ppm (measured as an annual average).

A.3 OZONE (O_3)

Ground-level ozone is the primary constituent of smog. It is not emitted directly by specific sources but created by sunlight acting on "precursor" gases such as NO_x and VOC in the air. People with impaired respiratory systems such as asthmatics are the most sensitive to the exposure, but healthy individuals can also be affected with symptoms like chest pain, coughing, nausea, and pulmonary congestion. Other environmental impacts are reduced agricultural productions and damages to forest ecosystems. The EPA sets the health-based national air quality standard at 0.12 ppm (measured at the highest hour during the day), but approximately 50 million people in the United States lived in counties with air quality levels above this standard in 1994.

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