USDOT Region V Regional University Transportation Center Final Report

NEXTRANS Project No 044PY02

Financial and Technical Feasibility of Dynamic Congestion Pricing as a Revenue Generation Source in Indiana – Exploiting the Availability of Real-Time Information and Dynamic Pricing Technologies

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TECHNICAL SUMMARY

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Introduction

Highway stakeholders continue to support research studies that address critical issues of the current era, including congestion mitigation and revenue generation. A mechanism that addresses both concerns is congestion pricing which establishes a direct out-of-pocket charge to road users thus potentially generating revenue and also reducing demand during peak hours.

Congestion pricing (CP) is based on the classical economic laws of supply of demand: the different prices imposed by CP for highway use at non-peak and peak periods can help regulate demand and manage congestion even with relatively little or no increases in supply. At times of peak demand, road users impose costs on each other. By making these users pay for the costs associated with the additional congestion they create, CP can encourage the redistribution of travel demand in space or in time, or both. Thus, CP harnesses the power of the market to reduce the waste associated with traffic congestion and ultimately helps to achieve more efficient use of transport infrastructure. Introducing CP on highway facilities discourages overuse during rush hours by motivating trip-makers to travel at other times of the day or to shift to other modes. By removing even a fraction of vehicles from a congested roadway, CP enables the system to flow much more efficiently, allowing more cars to move through the same physical space.

A review of the literature on CP theory and practice indicates that congestion pricing can and does result in substantial benefits including congestion mitigation, modal shifts, revenue generation, and decrease in energy consumption and air pollution. Worldwide, roadway CP has been applied at London, Milan, Singapore, and Stockholm. Also, the CP concept, where users pay variable charges depending on the demand for a service at any given time, has been successfully utilized in other industries such as airline tickets, telecommunications, and electricity.

Congestion pricing analysis has traditionally been divided into two models: the static and the dynamic models. The static model, first introduced by Alan Walter in 1961, has served as the standard model of static first-best best pricing until recent times. Due to its simplicity, the static model helps economists to "sell" the concept of congestion pricing; however, it is plagued with implementation barriers as demonstrated over the past decade: the toll can help mitigate congestion but the road user may end up being worse off by incurring a higher travel cost. The dynamic model, developed towards the end of the last century, helps overcome the limitations of the static model and is more practical. However, the dynamic model is complicated and has extensive data requirements compared to the static model.

The report traces the evolution of the concept of CP over the past millennium; explains why CP implementation continue to be limited at the current time; establishes user cost functions and traffic equilibrium conditions associated with the static and dynamic models, for a number of implementation scenarios including 1-free-route only, 1-free-and-1-tolled route, and 2-tolled-routes; applies these models in a case study that uses data from a congested 6-mile section of Interstate 69 in Indianapolis; uses the case study to evaluate the benefits of CP at the selected corridor; and assesses the CP economic efficiency on the basis of capital costs, operating and maintenance costs, and toll revenue.

Findings

In the case study, the base case is that the agency builds a new lane and leaves both routes free. Then the impacts of tolling the new lane but leaving the old route free, was evaluated, for both static and dynamic pricing scenarios.

Regarding the static second-best pricing of the tolled new route only and the free existing route, it was found that relative to the base case, the average user cost is 2.5% higher that than of the base case. The total consumer surplus is lower compared to the base case. However, the increase in the social surplus of the system increases (and even offsets) the reduction in consumer surplus. Due to the reduction in consumer surplus and increase in user cost, the number of vehicles that use the system decreases. There is only 3% system efficiency. It was also determined that in order to maximize social welfare, the agency will need to impose a flat toll of $1.72. Overall, compared with the base case, road users are left worse off.

With regard to the dynamic second-best pricing of the tolled new route only and the free existing route, it was estimated that relative to the base case, there would be a 4.6% reduction in average user cost, increase in traffic volume, reduction in the duration of the peak period, and 30% system efficiency. Also, no road user is left worse off and there is an increase in consumer and social surpluses. The variable toll on the tolled route, which is set at a level that is equal to travel delay cost, starts from 0 at beginning of peak hour, increases to a maximum of $9.75 and decreases to 0 at the end of the peak hour. In determining the value of flat toll that is consistent social surplus maximization, a negative value was obtained; thus, the agency will need to subsidize each vehicle’s toll to some extent.

Recommendations

The results throw more light on the feasibility of congestion pricing as a strategy for congestion mitigation and a source of revenue generation in a fast-growing urban freeway corridor in the City of Indianapolis. It is recommended that the agency considers the implementation an experimental pricing scheme at this location or other location selected by the agency. A new, parallel lane could be constructed and tolled. Dynamic second-best pricing could be used to design the toll for the new route. The implementation could be preceded and also accompanied by a large dose of publicity to the effect that it is not permanent but a pilot scheme, and the potential benefits of the system should be made to receive extensive publicity. These stated benefits could include reduction in average user cost, increase in throughput, reduction in the length of the peak duration, increase in overall system efficiency, and increase in consumer and social surplus. The analytical framework developed in this report could be used by the Indianapolis Department of Transportation and other highway agencies to identify the expected impacts of different scenarios and schemes for congestion pricing application at future candidate locations.

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CHAPTER 1 INTRODUCTION

This introductory chapter is divided into four subsections. The first presents the study background and the second discusses the evolution, since the days of Adam Smith, of the background concepts associated with congestion pricing. The third presents public attitudes with regard to road pricing and the fourth identifies the three broad contexts for congestion pricing. The last subsection provides an outline of the report.

1.1 Study Background

The report by the National Surface Transportation Policy and Revenue Commission (2007) establishes the need for a significant increase in public funding in transportation. The report also recommends that appropriate pricing mechanisms be studied for subsequent implementation to help pay for the use of the system. The fuel tax based financing system has served the nation well for several decades and indications are that it cannot continue any more as society seeks to conserve petroleum resources and search for new transportation energy sources. One of the several financing initiatives that can be considered is congestion pricing. Congestion pricing, which is the establishment of a direct out-of-pocket charge to road users, not only generates revenue but also is a way of harnessing the power of the market to reduce the waste associated with traffic congestion thus inducing more efficient use of transport infrastructure. Introducing congestion pricing on highway facilities can discourage overuse during rush hours by motivating people to travel by other modes such as carpools or transit, or to travel at other times of the day. By removing a fraction (even as small as 5%) of the vehicles from a congested roadway, congestion pricing can enable the highway system to flow much more efficiently, allowing more cars to move through the same physical space.

1.2 Evolution of Congestion Pricing

Lindsey (2006) described the evolution of congestion pricing over the years. The idea of road pricing has existed for at least two hundred years. In a seminal publication titled “Wealth of Nations”, Adam Smith suggested that for a self-supporting road network, horse-drawn carriages that were using the roads at that time should pay tolls commensurate to the amount of damage they caused to the roads. Also, believing that the private sector could operate and maintain the road facilities in a better way compared to the government, Adam Smith was an ardent proponent of private sector involvement in road management (Smith, 1776). Another influential and precocious thinker of that era was Jules Dupuit, a French engineer whose work has been reviewed by Ekelund Jr. and Hebert (1999). Dupuit considered road pricing as more of a cost-recovering tool than a traffic congestion mitigation strategy. Having derived the idea of cost recovery and profit maximization of the monopoly, Dupuit advocated for the use of price discrimination to boost revenue, and thus was a pioneer of the concept of average-cost pricing. Dupuit also recognized the problem of traffic diversion: if a road or a bridge is tolled, traffic tends to divert to free routes thus causing congestion on the latter.

The early 20th century. During this period, Arthur Pigou initiated the idea of using road pricing to manage congestion (Pigou 1920). In his most well-known paper “The Economics of Welfare” which considered two parallel routes, Pigou argued that for two existing parallel routes from a given original to a given destination, traffic would divert between them until their conditions were equally worse; in such a situation, it is possible to shift traffic, through taxation, from one route to another and to minimize the damage to the latter; nevertheless. After Pigou, relatively little work was carried out during the early part of the subsequent century. Frank Knight (1924) criticized Pigou’s work, asserting that a superior condition could be reached without taxation. Clark (1923) argued that the toll charged to users should be commensurate with the level of road damage they caused, a position supported by Peterson (1932) who suggested that roads should be treated and priced as is done for other commodities. From a more balanced position, Buchanan (1952) discussed the merits and demerits of road tolling, and concluded that tolling has a potential to improve traffic levels of service and to reach the goal of optimal use. Before the middle of 20th century, Nobel laureate Ronald Coase published “The Marginal Cost Controversy,” a paper that advocated self-financing of systems (even though roads were not explicitly addressed in the paper) (Coase 1946). Coase believed that average-cost pricing is preferable to marginal-cost pricing with subsidy.

Mid-20th century. It was during this time that the concept of congestion pricing started to take shape. A pioneer during this period, William Vickrey, published approximately forty papers on congestion pricing within the period 1984 to 1996. His pioneering paper, “Some Objections to Marginal-Cost Pricing” presented two critical concepts that later become widespread in this area of research (Vickrey 1948). The first was that price should be set at the short-run marginal cost rather than the long-run marginal cost or average cost. The second was that as demand fluctuated, price should be adjusted to match the short-run marginal cost as closely as possible. Another key player was Alan Walter who agreed with Vickrey that price should be set at short-run marginal cost. Walter’s widely-cited paper, “The Theory and Measurement of Private and Social Cost of Highway Congestion” (Walters 1961), which is considered a landmark in congestion pricing studies, introduced the basic static congestion pricing model (further details of which are provided in Chapter 2 and Figure 2.4 of this report). Walter’s concept helped economists “sell” the idea of congestion pricing idea in the decades that followed. Also, Walter’s model presented the other perspective of congestion pricing: changes in individual travel cost and impacts (or lack thereof) of traffic congestion. Unfortunately, the supposed simplicity of the Walter model has been grounds for criticism from researchers such as Small and Chu (2003) who argued that the Walter model is unable to adequately account for the hyper congestion state of traffic, the realistic and day-to-day situation in most urban areas in the current era. In 1962, Mohring and Harwitz (1962) derived the “Cost Recovery Theorem” that strongly buttressed the position of short-run marginal-cost pricing. The theorem, which stated that the revenue from the short-run marginal cost pricing would be enough to pay back the optimal capacity, is based on the assumption that capacity is perfectly divisible and can be supplied at constant marginal cost and that user cost is homogeneous. During that era, the UK Ministry of Transport established a panel of experts to examine road taxation and this culminated in the 1964

Smeed Report whose contents were similar to the Vickrey results but presented a more practical view of road pricing (Transport, 1964).

Late 20th century. It was not until the end of the 20^{th} century that congestion pricing concepts matured and became practical. This period saw an explosion in the amount of published research on the subject. The dynamic congestion model was also developed during this era and the cost-recovery theorem was examined in great detail during this period. The main result was the recommendation that tolls should be collected in such a manner that is commensurate with the sum of congestion and physical damage to the road and that the toll should adequately cover the optimal capacity and the maintenance cost. Researchers examined the issue from other angles and sought to identify the conditions that promote efficient pricing in the implementation (Arnnott and Kraus (1998)), finding that “the anonymous link tolling is efficient if tolls can be varied freely over time,” thus encouraging the idea of short-run marginal cost pricing (Lindsey 2006).

1.3 Why Congestion Pricing Applications Continue to be Limited at the Current Time

As pointed out by at least one researcher, congestion pricing applications continue to be limited at the current time for a number of reasons (Lindsey 2006). First, the concept of congestion pricing continues to generate significant controversy even though economists generally seem to agree that pricing should be used to manage traffic congestion. This section discusses a number of viewpoints associated with this conundrum.

An ongoing controversy is the relative merits of the marginal short-run cost pricing and average pricing schemes. The former guarantees optimal usage of the road system but does not guarantee that all associated costs will be recovered. On the other hand, average pricing can achieve cost recovery but is not necessarily optimal. Lindsey and Verhoef (2000a) discussed other more complicated aspects of congestion pricing, namely, road network pricing, heterogeneity of road users, stochastic congestion pricing, private road pricing and interaction with other sectors. The researchers also discussed the difficulty of implementation from social and political perspectives.

Analysis of the economics of private toll roads is another area of research often seen as distinct from the other literature. Issues associated with this area of research include the appropriate form of ownership, type of toll regulation, or the exercise of (monopoly) power. As stated in past research, the largest concern regarding private toll roads is the lack of competition in the road market that culminates into a monopoly situation. Monopoly is often characterized, unfortunately but quite expectedly, by toll increases to inefficient levels in a bid to maximize revenue. On the other hand, proponents of private toll roads argue that the private sector has a greater incentive to operate efficiently, to identify appropriate technology to reduce costs, and to improve service quality. Moreover, they assert that there is no guarantee that the government will never increase the toll to levels that are above the efficient level. Admittedly, there could be situations where the government itself might be lured into seeking generating large revenue by imposing higher tolls on public roadways.

Second, the implementation of pricing only at selected roads in a parent network may not be optimal due to fluctuation of traffic in the system and the differentiation of user cost. Researchers have argued that this is really not optimal because traffic tends to divert to other roads. A similar argument is made for cordon area pricing (satellite-enabled tolling technology might help address this problem. It is precisely for these reasons that the concept of “second best pricing” was developed.

Third is the difficulty of calculating the right toll amount. Demand fluctuation, cost prediction, and travel time values are all hard to predict with adequate certainty. Even the simplest static congestion pricing requires knowledge of the appropriate demand and supply functions which are difficult to obtain. Verhoef and Small (2004) presented a possible solution that uses the idea of trial-and-error pricing. Their step-by-step in-service field method involves a gradual and incremental increase in the toll amount (without undue inconvenience to the road users) to identify the amount that yields an optimal speed of the road users.

Finally, there is the issue of equity. Congestion pricing has been criticized as a regressive tax policy: users who mostly benefit (or are expected to benefit) from congestion pricing implementation high-income users whose have a relatively high value of travel time. However, it can be argued that if the toll revenue is well spent, the overall outcome may very well be consistent with a progressive tax: the funds collected from the system could be invested in the roadway to further increase the level of service to all users or could be invested in public transit. Options to allocate this revenue could be controversial, particularly in situations where the citizenry has little trust in government management of collected revenue.

1.4 Literature Review

The review of relevant literature in this section is divided into three subsections: the cost function, static congestion pricing, and dynamic congestion pricing. The cost function is the important foundation for congestion pricing analysis. The static congestion model is relatively easy to comprehend and paves the way for the dynamic model. The dynamic model is more complicated but is more consistent with the reality of current-day congestion. Appendix A presents literature that is not mentioned explicitly in this chapter but is associated with these issues.

The cost function is the basic foundation of any congestion pricing analysis. Thus, this report starts the discussion of the user cost function (see Chapter 2 of this report). The cost function comprises the fixed and the variable parts. The variable part varies with the level of congestion; the manner in which this part is modeled is what drives the distinction between static and dynamic congestion pricing. Static congestion pricing is developed from the time-independent traffic model while dynamic pricing is developed from the time-dependent traffic model. Hall (2003) discussed the theories of traffic modeling, including queuing theory that uses the bottleneck model (Chapter 5 of this report) and traffic flow theory (Chapter 6 of this report). McCarthy (2001) and Small and Verhoef (2007) discussed the production and cost functions in the transportation context (see Chapters 5 and 6 of this report, for McCarthy (2001); and Chapter 3 of this report, for Small and Verhoef (2007)).

As stated previously in this chapter, static congestion pricing was first introduced by Alan Walter (1961) as a “conventional diagram” or as currently known, the static first-best pricing scheme. The static model starts with the link performance function that represents the traffic condition of the road in question. The link performance is converted to the variable user cost by multiplying the travel time with the time value of the road user. This user variable cost fluctuates due to varying traffic conditions. The addition of the variable user cost to the fixed cost function yields the cost function for the analysis. The background literature for this analysis includes Lindsey and Verhoef (2000b); McCarthy (2001); Button, 2004; Small and Verhoef (2007).

After the user cost function is obtained, the optimal toll of a road is derived (Chapter 3 of this report). However, a perfect setting of the first-best congestion pricing model is hard to implement in reality. Some implementation restrictions need to be enforced, thus, moving the toll from the optimal level associated with static first-best pricing. To solve the problem of optimality, economists have introduced the second-best pricing scheme. In recent decades, many publications have introduced many kinds of second-best pricing schemes. The most common of these is the “two parallel competing” routes of which only one is priced. This is discussed in detail in Chapter 3.

Verhoef and Nijkamp (1996) studied the second-best pricing scheme using the static traffic model and linear elastic demand. The paper included both the optimal social surplus toll and the maximized toll. The two-route parallel pricing on a selected route was presented and used to compare across toll alternatives; and the writers introduced an index that was adopted in subsequent publications to assess the efficiency of pricing schemes. The paper also studied the influence of a number of cost and demand parameters on the efficiency of a toll system. An interesting result is that two-route revenue maximizing toll (i.e., where the other route was left free) was found to be more efficient than one-route optimal tolling. The intuition is that in certain cases, it is better to have monopoly control over all entire network than over only a part thereof. However, when the elasticity of demand is low, a private monopoly would tend to increase toll above the optimal level. Moreover, even if the pricing scheme is found to be efficient, there is no guarantee of effective implementation of the scheme via efficient revenue collection. This concept has been discussed by Lindsey and Verhoef (2000a); Rouwendal and Verhoef (2004); Small and Verhoef (2007).

In analyzing congestion pricing, it is often sought to identify the optimal toll amount and the optimal level of capacity. Generally, the highway travel mode is considered to be underpriced: such under pricing, from the optimal perspective, influences the optimal level of capacity. Wilson used the static traffic model to study this issue, and found that lower-than-optimal pricing leads to a decrease in the optimal capacity if price elasticity is adequately high (Wilson, 1983). However, if the price elasticity is lower than the ratio of consumer price of travel to the private congestion cost, the result is the opposite. Also, D'Ouville and McDonald (1990) explored the level of optimal road capacity of second-best and first-best price settings using the static traffic model. The two parameters that were found to affect capacity are the price elasticity of demand (from the demand curve) and the elasticity of substitution of consumers' travel time (from the cost function).

In the current era, the static model is still used even though it was developed several decades ago. The static model is easy to understand and helps promote the idea of congestion pricing. However, two main limitations of the static model are that it cannot represent the hyper congestion traffic condition and cannot handle the variable toll (or fluctuations in traffic over time). The dynamic model, a solution to these limitations, is discussed in the next section.

Dynamic congestion pricing. As stated previously, the idea of congestion pricing has long existed but it was not until the late 20th century that the dynamics model of congestion pricing started to take root. Braid (1989) studied congestion pricing in the single bottleneck model with the elastic demand and derived the amounts of variable tolls during the peak hour and the uniform toll for the entire peak hour. Arnott and Palma et al. (1990) provided a complete analysis of the economics of the single bottleneck model during a peak hour; a fixed number of road users (vehicles) during the period was assumed (that is, the case of inelastic demand) and provided both the optimal toll and capacity level, for two types of pricing schemes.

Arnott and Palma et al. (1993) provided a full analysis of traffic assignment between for the "2-route parallel" for congestion pricing analysis. The dynamic bottleneck model was used to analyze the peak hour demand, and the researchers described the development of user equilibrium and the system optimal in various level of traffic in the congestion pricing setting. They also used the single-route bottleneck model to compare three toll alternatives and one free access: variable toll, course toll for the entire peak hour and 1-step toll during the peak hour. The researchers compared the traffic condition, social surplus and the optimal level of capacity among alternatives.

Braid (1996) and Palma and Lindsey (2000) analyzed the second-best congestion pricing in the "2-route parallel" setting using the dynamic bottleneck model with elastic demand and presented both the optimal toll and traffic assignment. The pricing schemes included 2-route free accesses, 1-tolled and 1 free access, and both roads tolled. In addition to Braid, Palma and Lindsey provided the social optimal toll (which reflects the agency's point of view) and the revenue maximization pricing scheme (which reflects the private sector's viewpoint).

For the 2-route parallel problem, the analysis could be extended to the two competing travel modes. Arnott and Yan (2000) presented an overview of second-best pricing in the "2 competing travel modes" scenario and identified the second-best price setting and the optimal capacity. For example, there were options to travel from the origin to the destination by rail transit or other modes or roads. A review of relevant papers on the subject is provided in Appendix A.

1.5 Outline of the Report

This report comprises seven chapters. Chapter 1 provides the evolution of congestion pricing and introduction of concepts. In Chapter 2, the user cost function theory, an important foundation of congestion pricing, is provided. The chapter also lays the grounds for static congestion pricing, and ultimately, for dynamic congestion pricing. Chapter 3 discusses the dynamic congestion pricing using the bottleneck traffic model. The fourth chapter presents a numerical example to help comprehend the implementation of relevant economic theories. Chapter 5 shows the result of the analyses and discusses these results. The sixth chapter carries out a simplified financial feasibility analysis to ascertain the extent to which the toll revenue can cover capital and operating costs. The last chapter summarizes and concludes the study. Appendix A provides a categorized review of literature in the field of congestion pricing and Appendix B presents existing congestion pricing projects in domestic and international settings.

CHAPTER 2 STATIC CONGESTION PRICING - (DEVELOPING THE STATIC USER COST FUNCTION AND OPTIMAL STATIC PRICING)

This chapter, which is divided into four sections, describes the theory of static congestion pricing. Section 2.1 starts with the basic static user cost function, a key preliminary input not only for the static congestion pricing analysis but also for the dynamic analysis. Section 2.2 introduces the static traffic modeling and the technique for developing the congestion cost model from the traffic model. Section 2.3 presents the classic theory of congestion pricing – the static first-best pricing or the marginal-cost pricing, and Section 2.4 analyzes the static second-best pricing. The classic 2-route parallel problem is presented. The background concepts and material for this chapter was drawn largely from Verhoef et al. (1996), McCarthy (2001), Button (2004), and Verhoef (2008).

2.1 Static User Cost Function

The cost function can be considered a key foundation for congestion pricing. As is demonstrated in this chapter, the optimal toll is the price corresponding to the marginal cost. Derivation of the function that actually represents the user cost of the system can enable the attainment of the system's optimality. However, it is rather difficult to derive this cost function. The static cost function is easy to comprehend and to interpret to the public. However, it is not optimal under conditions that change significantly with time, a situation that is addressed using the dynamic cost function. The inherent flexibility of the dynamic cost function is however accompanied by a relatively larger amount of input data needs and greater calculation complexity. This chapter focuses on the static function while the next chapter addresses the dynamic function.

In this section, the principal concept of the static user cost function is provided. The user cost function comprises two parts: the fixed component and the variable component. The fixed user cost does not vary with the traffic volume while the variable component varies with the level of congestion. In the user cost function, the fixed and variable costs are represented by c_0 and c_g, respectively. The variable cost component is often referred to as the congestion cost. Unlike the variable cost, the fixed cost is the same in the static and dynamic models. In the static model, the congestion cost c_g is derived as the product of the travel time amount (read-off from the link performance function) and the value of travel time. On the other hand, in the dynamic model, the congestion cost c_g is derived using queuing theory of bottleneck model. There exist other time-dependent traffic modeling technologies; however, in this report, the bottleneck model is used. The user cost function can be defined as follows:

$c = c_0 + c_g + \tau$ → (eq. 2-1)

where; c = average user cost for each road user (vehicle). In dynamic congestion pricing analysis, this term is not a constant but is expressed as $c(t)$.

c_0 = monetary cost which includes vehicle operating cost and free-flow travel time cost, assumed fixed (independent of the level of traffic congestion).

c_g = congestion cost, which depends on the level of traffic congestion. This term is what differentiates the static model from its dynamic counterpart.

τ = toll or out-of-pocket cost. This term represent only the flat toll in the static congestion pricing scenario; or both the flat and variable tolls in the dynamic congestion pricing scenario. The symbol τ as used here represents all tolls. As will be seen later in this chapter, the variable toll can be represented by V.

The basic concept expressed by Equation 2-1 can be represented by Figure 2.1.

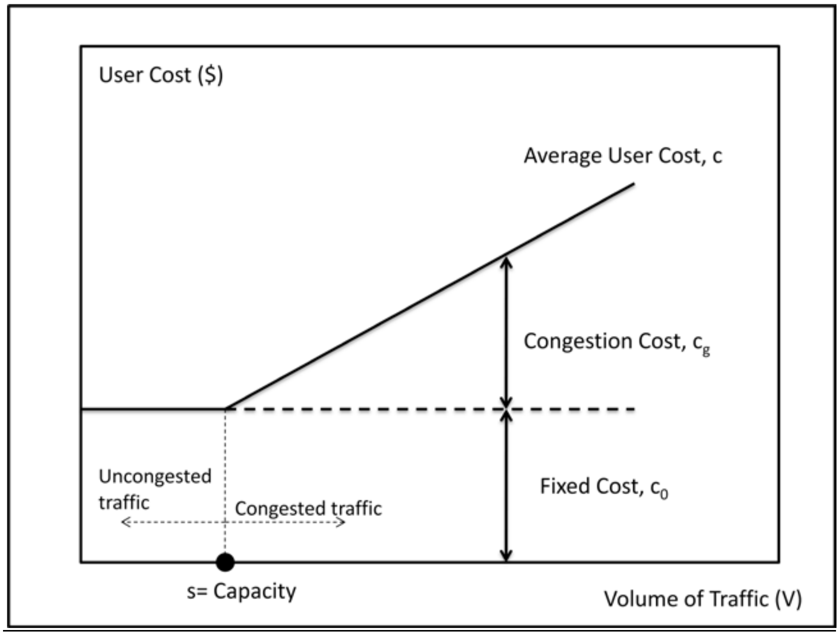

Figure 2.1: The user cost function

As seen in Figure 2.1, the total user cost comprises the fixed cost c_0 and the congestion cost c_g. The latter varies with the traffic level. Before the traffic level reaches capacity, all vehicles drive at free-flow speed. After the traffic level exceeds capacity, congestion cost increases with increased travel time.

The above discussion lays the basis for the user cost function. Regardless of the level of complication of the traffic model, the user cost function can be the same across static and dynamic scenarios: the main difference is the function chosen to model the congestion cost c_g, if any.

2.2 The Static Traffic Model and User Cost Function

In this section, the user cost function is derived using the static traffic model. As stated early in the previous section, it is the term congestion cost c_g that drives the distinction between the static model and the dynamic model. The steps taken to build the congestion cost are as follows:

- The static traffic model means the time-independent traffic model. It cannot incorporate trip re-schedulers (i.e., road users who enter road system early or late in a bid to avoid congestion) into the model. Thus, the average of traffic conditions over the entire period of interest (i.e., peak-hour) is considered.
- This report uses the time-averaging traffic model to develop the congestion cost.
- The time-averaging model represents the level of the congestion due to the number of vehicles using the system during the entire peak hour. This type of static model considers the level of congestion by averaging the traffic condition throughout the entire peak-hour period.
- First, the link performance function of the road section of interest needs to be developed. Several forms of link performance functions are available, such as:
    - $S = S^f (1 - D/D^f)$ → (Greenshield 1935) → Static flow
    - Speed-flow curve $S = a + c\,(V/V_k)^b$ → (HCM 2000)
    - $T = \quad (1 + a\,(V/V_k)^b)$
- This report uses the linear piecewise model to represent the traffic condition of the road section of interest:

$T = \qquad$, if $N < s$

$\;\; = \quad + a\,N/s$, otherwise →(eq. 2-2)

Where;

T = travel time for the road section

= free-flow travel time for the road section

N = total number of vehicles during the peak hour

s = the road capacity

a = a constant value.

The linear piecewise model, that is, the time-averaging traffic model, was chosen in this report for a number of reasons. First, this model can be easy to compare with the dynamic traffic model as will be seen in Chapter 3. The time-averaging traffic model has the number of vehicles for the entire peak period as the output; this is similar to the dynamic traffic model. Also, the linear piecewise model can be considered as a reduced form of the dynamic bottleneck model. These details are discussed in detail in Chapter 5.

Further details of the linear piecewise (or time-averaging) traffic model are presented in Small and Verhoef (2007). Figure 2.2 describes the linear piecewise traffic function (equation 2-2).

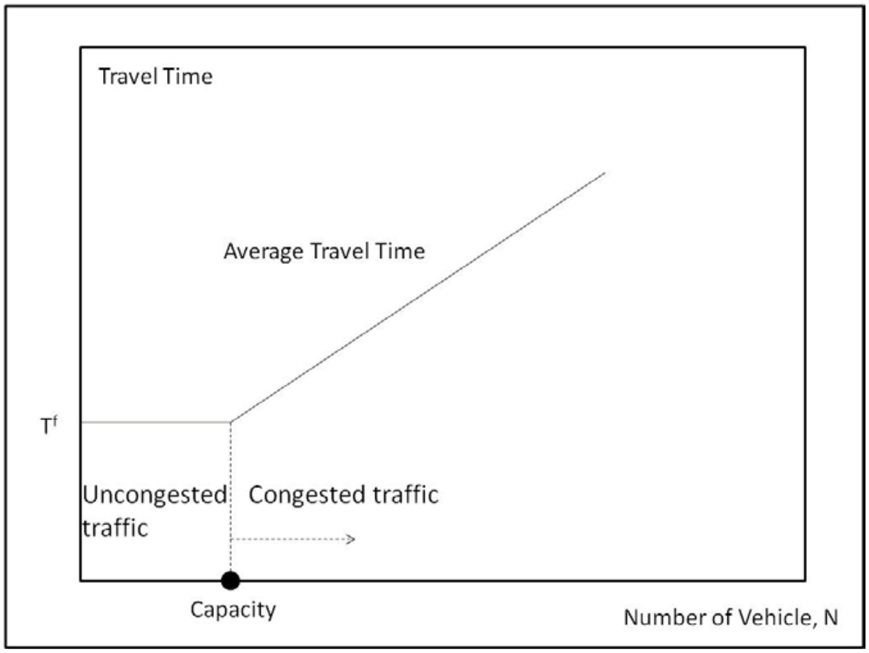

Figure 2-2: The linear piecewise link performance function.

From Figure 2-2, the following observations can be made:

- The traffic starts to congest after the number of vehicles exceeds capacity. The travel time increases linearly with the number of vehicles with slope *a*.
- The value of slope "*a*" is not provided here. As will be seen later in this chapter, this linear piecewise static model can be considered as a reduced form of the basic bottleneck model. The value "*a*" is derived in a subsequent chapter of this report.
- After the link performance function is developed, the travel time is determined from the function, and the product of the travel time and the travel time value, added to the toll, yields the user cost function.
- Thus, the average user cost function is:

$$c(N/s) = c_0 \quad \text{, if } N < s$$

$$= c_0 + \alpha.a.(N/s) + \tau \quad \text{, otherwise} \quad \rightarrow \text{(eq.2-3)}$$

Where;

$c(N/s)$ = average user cost as a function of N/s

c_0 = the fixed cost = vehicle operating cost (VOC) + α

α = uncongested travel cost (cost of travelling on uncongested road)

α = travel time value in $/hr.

τ = flat toll

= free-flow travel time for the road section

N = number of vehicle during the peak hours

S = road capacity

The term ($\alpha .a.N/s$) is the congestion cost c_g.

The average cost obtained using equation (2-3) is multiplied with the total number of road users (vehicles) to obtain the total cost. Thus, the total user cost is:

$$C = N.\, c\,(N/s) \quad \rightarrow \text{(eq. 2-4)}$$

Now, the marginal user cost (MC) is defined. This is subsequently used in pricing analysis. The marginal cost can be calculated as:

MC = — = —— = c + N — = c + mecc →(eq. 2-5)

From equation 2-5, the marginal user cost is equal to the user average cost plus the term Nδc/δN (also referred to as the "Marginal Externality Congestion Cost (MECC)". Due to MECC, the user marginal cost deviates from the average cost under congestion conditions. If there is no congestion, MECC = 0 and the average and the marginal externality cost are equal.

The assignment of a value of zero to MECC when there is no congestion, can be explained. From equation 2-5, MECC = N— ——————— (here the average is substituted from equation 2-3). In this case, all terms are constant with the exception of c_g(N/s). The parameter c_g increases only when traffic flow causes the travel time T to exceed the free flow travel time . Figure 2.3 explains graphically the difference between the user average cost and the user marginal cost.

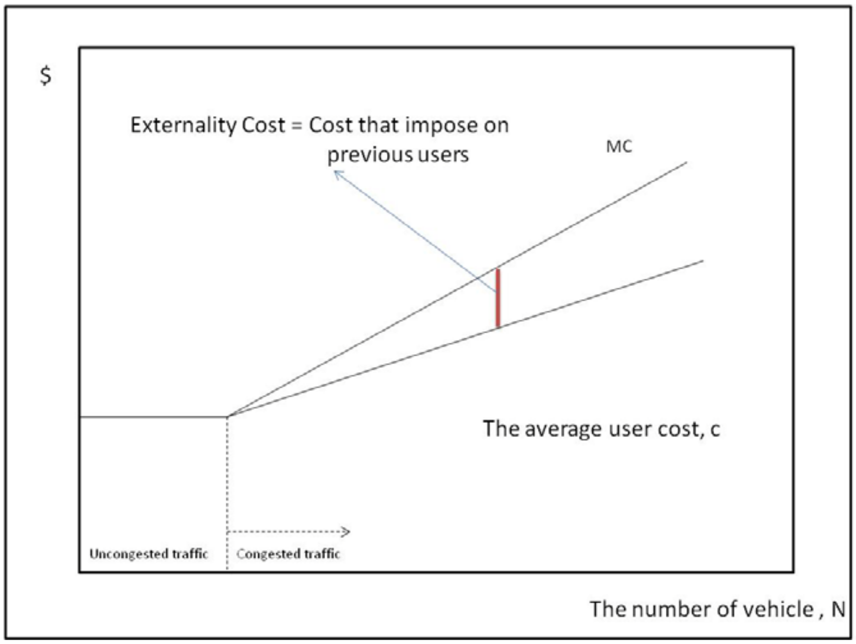

Figure 2.3: User cost from the linear-piecewise static traffic modeling

Next, this section introduces the classical form of pricing called "First-best Pricing" or Pigouvian Toll. As the name implies, this is the pricing scheme that yields the maximum social benefits. However, this is rather difficult to implement in the real world. As such, there might be a need to impose some constraints or limitation to the pricing plan. In efforts to do so, the resulting pricing plan is termed the "Second-best Pricing".

2.3 The Static First-best Pricing (Pigouvian Toll)

This pricing scheme can be viewed as a reference point because this is considered the best way that any road can be priced. The first-best pricing scheme "moves" the road system to the point where it provides the highest possible social welfare. This pricing scheme encourages users to use the road efficiently. The traffic congestion is not completely eliminated but it is reduced to a point that is consistent with maximum social benefits. Subsequent paragraphs present the details of this pricing scenario mathematically and graphically.

The derivation of first-best pricing toll is based on social welfare maximization. Social welfare is measured as the aggregate benefits to all users minus the user cost. From neoclassic microeconomics, the consumer benefit is equal to area below the inverse demand curve and above the price customers/road users need to pay for the service. Then, it is herein shown how to maximize welfare using pricing as follows (Verhoef, Nijkamp et al. 1996; Small and Verhoef 2007):

Max $W = B - C$

$=$ $- N.\ c(N/s)$ → (eq. 2-6)

Where; W= social welfare

B= = social benefit of using road

= area below the inverse demand curve

p(N) = inverse demand as a function of N = marginal willingness-to-pay

$N.\ c(N/s)$ = user total cost

$c(N/s)$ = average cost as a function of N/s, N= total number of vehicles, s = road capacity

Then, 1st order condition to maximization (here the short-run cost function is used because capacity s is fixed in the short-run).

$— = 0 = p(N) – c(N/s) – V. —$

Thus, $p(N) = c(N/s) + N. —$ →(eq. 2-7)

At this point of the discussion, the road toll τ is introduced into the analysis. The demand curve is a reflection of the willingness to pay, and it is assumed that the road user does not pay more than their individual average cost (as a function) plus toll:

$p(N) = c(N/s) + \tau$ (= generalized price) → (eq. 2-8)

Also, from equation (eq. S-3);

$MC(N/s) = — = c\ (N/s) + V. —$ → (eq. 2-9)

Equating (2-8) and (2-9) yields:

$p(N) = MC(N/s)$ → (eq. 2-10)

$c(N/s) + \tau = c(N/s) + N. —$

Then, the toll is:

$\tau = N. —$ = mecc (marginal externality cost)

$= MC – c(N/s) = p(N) – c(N/s)$, (here MC intersect with demand curve)
→ (eq. 2-11)

It may be noted that at the market equilibrium, the marginal willingness-to-pay will be equal to the average cost function plus the toll amount. The graphical interpretation of these equations is presented in Figure 2.4.

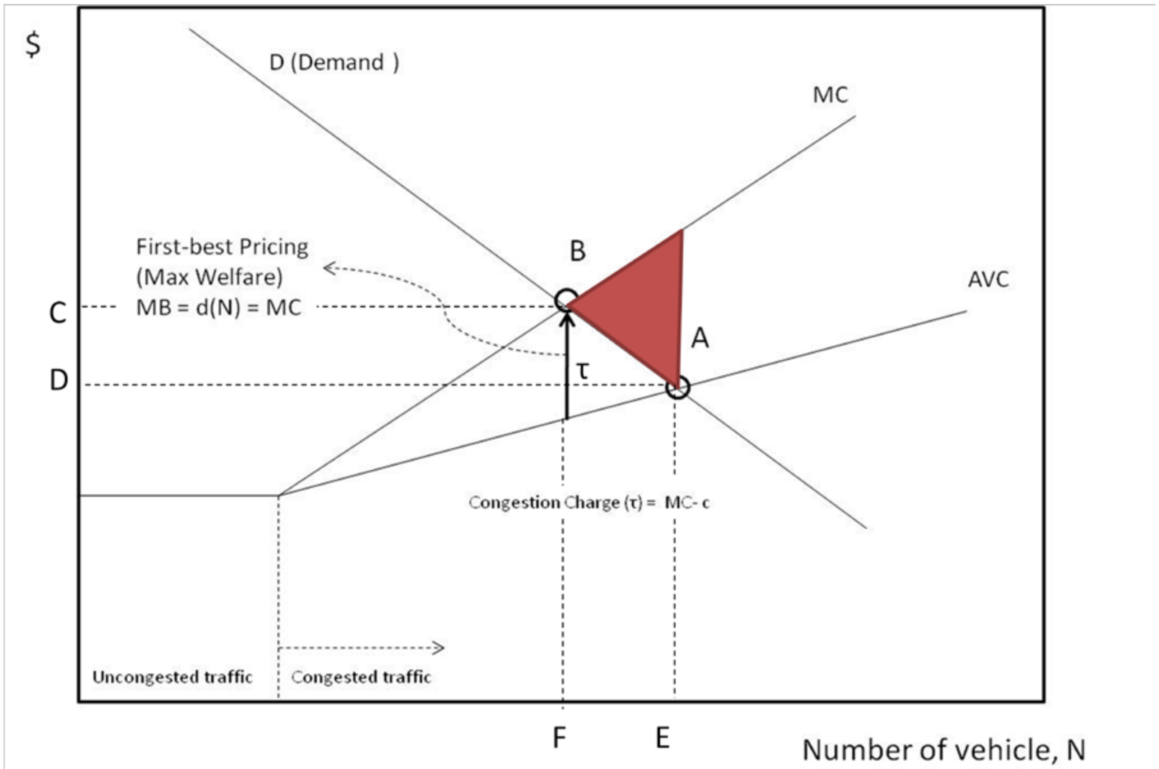

Figure 2.4: The First-best Pricing Scheme

Figure 2.4 shows that the demand curve cuts the cost curve at the congestion part. This indicates that without controlling the travel demand, the road facility will experience excess use. If this road is not priced, the equilibrium will be at point A. As stated previously, the users base their decisions on their individual user cost only. Here, point A is the market equilibrium; Demand = average user cost. This is not the optimal point of using the facility. Equation (2-10) states that demand has to be equal to the MC marginal cost in order to be optimal from the social welfare perspective. The point B represents the optimal point, and this is the so-called "Marginal Cost Pricing Rule". To force the system to point B, the toll τ is introduced to the system; this pushes the generalized cost of users up to point B. The length of the arrow in the graph is equal to the amount of optimal toll τ that is charged (Small and Verhoef 2007).

A relevant issue at this stage of the discussion is the nature of the relationship between Equation (2-10) and Figure 2.4. The marginal cost equal to the demand/

marginal benefit will promote social welfare maximization. The point B in Figure 2.4 is represented by Equation (2.10). From Equation (2-11), the toll that encourages the attainment of maximum social welfare is the gap that pushes the average cost c(N/s) up to point B in Figure 2.4.

Another relevant question is the effect of implementing the toll. This implementation will make system to be pushed back to the optimal level at point B. On average, the user ends up with paying a higher trip cost (which equal to C-D), however the entire system gains benefit that is represented by the shaded triangular area shown in Figure 2.4. This is the case because the individual only considers their individual cost but does not consider congestion cost (or MECC) that is imposed on other users. This is confirmed by the location of the marginal benefit at point A as being lower than the marginal cost. The marginal benefit is the inverse demand curve. It may be thought that by producing one more unit of service (allow one more vehicle to use the system), the marginal cost is higher than the marginal benefits. This is the loss of the system. In other words, the loss of the system is equal to the area of marginal cost above the marginal benefit curves, which is represented as the shaded triangle in Figure 2.4. By pushing the system equilibrium back to point B, this loss area becomes the benefit gain of the system: congestion is reduced; and the traffic volume decreases from E to F (Small and Verhoef 2007).

It may be noted from Figure 2.4 that the inverse demand function was used. This is actually similar to the normal demand function. In the classical microeconomic theory, the demand function is formally defined as the reduction in quantity demanded (potential number of consumers) due to the increase in price. That is, the amount of dollars is the explanatory variable (or x-axis) and the number of consumers is the dependent variable (or y-axis). In the context of this study, the x-axis is the number of consumers and the y-axis is $. Therefore, theoretically this can be referred as the inverse demand function. Technically, the inverse demand and the demand function can be used, and have been used interchangeably in most literature (Nicholson 2002).

The steps in calculating the toll amount for the First-best Pricing scenario are listed herein:

- Estimate the demand curve
- Estimate the user cost function
- Equate the inverse demand curve and the marginal cost as in equation (2-9). To derive the toll amount to be charged, solve the estimated demand and average cost together. For a single road and single time period, there is only 1 toll value τ.

  $p(N) = MC$ and $\tau = p(N) - c(N/s)$

2.4 Static Second-best Pricing

The first-best pricing is optimal. However, due to its lack of practicality, there is a need for other types of pricing scheme. The first-best pricing assumes that an agency could price every segment of market at the marginal cost. For example, the marginal cost for trucks and passenger cars are different. However, in reality, the marginal cost of rush-hour and the night time can be very different. First-best pricing can only be implemented if all these market segments can be separated effectively.

The transition between the first-best and the second-best pricing scheme can be facilitated by a discussion of the three types of price discrimination theory. This theory discusses the use of monopoly power by firms to disaggregate the market into many groups and to price them differently due to the differences in the amounts of their willingness-to-pay. The underlying purpose is to capture, as much as possible, the consumer surplus in the market. However, the limitation of this theory is its inability to prevent the “Arbitrage Opportunity”, that is, the inability to separate customers and prevent the resell. For this reason, and also because it is difficult to implement the perfect price discrimination in the real world, the second-best pricing scheme is needed. More importantly, it is not considered feasible to implement the “Lump-Sum Tax” in the real world to fund a highway system. The lump-sum tax theory states that, to maximize the social utility, it is better to tax people at the income instead at the particular goods or services. Thus, second-best pricing seems to be a better option for road pricing.

In second-best pricing, the objective function is set up similar to that for first-best pricing. Only a few constraints are added to the analysis. The classic problem (2 parallel routes with perfect substitute) is introduced: one route is tolled, the other is not. This assumption can be relaxed as will be seen later in this chapter. For example, a highway competes with a light-rail line. This can be analyzed as two parallel routes but not as perfectly substitutes. The problem can be modeled as follows:

Max $\quad - N^A c^A(N^A/s^A) - N^B c^B(N^B/s^B)$ →(eq. 2-12)

St. $p(N^A + N^B) - c^A (N^A) = \tau^A$ →(eq. 2-13)

$p(N^A + N^B) - c^B$ (Berenbrink and Schulte) = 0 →(eq. 2-14)

where; Subscribe A, B = tolled and untolled routes, respectively

= area below the inverse demand curve

$p(N)$ = inverse demand = marginal willingness-to-pay

$N.\ c(N)$= user total cost

$c(N)$ = average cost

N = the number of vehicles during peak hour

τ = toll on tolled road A

The Lagrangian multiplier can be used to solve this problem as follows:

$$L = [\quad - N^A c^A(N^A/s^A) - N^B c^B(N^B/s^B)]$$

$$+ \lambda_A [c^A(N^A/s^A) + \tau^A - p(N^A + N^B)] + \lambda_B [c^B (N^B/s^B) - p(N^A + N^B)] \rightarrow \text{(eq. 2-15)}$$

The 1st order necessary condition of maximization is that the derivative of L with respect to N^A, N^B, τ, λ_A , and λ_B are equal to zero. Solving all these derivative equations yields:

$$\lambda_A = 0 \rightarrow \text{(eq. 2-16)}$$

$$\lambda_B = (N^A.\ c^A{}_N)/ (c^B{}_N - p_N) \rightarrow \text{(eq. 2-17)}$$

$$\tau = N^A.\ c^A{}_N + N^B.\ c^B{}_N (p_N)/ (c^B{}_N - p_N) \rightarrow \text{(eq. 2-18)}$$

The $c^A{}_N$ and p_N represent the partial derivative of c^A and p(N) with respect to N.

From the maximization problem (2-12 to 2-14), the result is presented in equation (2-16 to 2-18). First, the shadow price of the toll road equal zero (equation (2-16) the λ_A

= 0). This is the expected result because in this problem the toll is set at the level of maximum social surplus (objective function). Mathematically, this shadow price λ_A is an indication of the change of objective function (social surplus) due to one unit change in the right hand side of toll road's constraint (toll τ) (Verhoef, Nijkamp et al. 1996; Small and Verhoef 2007).

Second, the shadow price of the untolled road $\lambda_B \neq 0$. This means that if this constraint (equation S-13) were relaxed, or if toll were allowed on this road, the objective function or the social surplus will increase by the amount $\lambda_B = (N^A. c^A_N)/ (c^B_N - p_N)$. This emphasizes the previous discussion that the surplus of second-best pricing scheme will be less than or equal to that of first-best pricing scheme. That is, if the second-best pricing system were implemented on both roads at the maximum surplus level, the second-best pricing will become the first-best pricing (Verhoef, Nijkamp et al. 1996; Small and Verhoef 2007).

Third, the toll collected on one road is shown in equation (2-18). The first term is the MECC (marginal externality cost) similar to the first-best pricing scheme. However, in this case, there is another term, $N^B. c^B_N (-p_N)/(c^B_N - p_N)$. This second term is the price that the agency adjusts for traffic that spills over to the untolled road. For a clearer explanation, consider two extreme situations and one normal situation: first, if the demand is perfectly inelastic ($p \rightarrow -\infty$), then the fraction term becomes equal to 1.0 and the second term becomes equal to the MECC of the untolled road; that is, the toll is equal to the difference between the MECC of tolled and untolled roads. All trips that diverted from the tolled road will go to the untolled road. Secondly, if the demand is completely elastic ($d' \rightarrow 0$), then the second term will become equal to zero. The best way to price the tolled road is to use the first best pricing: trips that divert from the tolled road will not go to the untolled road but would find another alternative route such as other minor roads or a different mode of transportation to undertake the trip. Third, if the demand elasticity is not extreme as discussed, the fraction will less than 1; some trips that divert from the toll road will use the untolled road, while others will use other minor routes or different modes. This proportion depends on the elasticity of demand (Verhoef, Nijkamp et al. 1996; Small and Verhoef 2007).

There exist a number of different types of second-best pricing, all of which share the same objective function but different constraints due to variety in their contexts. The Appendix provides a list of literature in this regard.

The next chapter discusses dynamic congestion pricing. However, the concept of static congestion pricing is revisited in a subsequent (modeling) chapter. The actual traffic values and the assumptions are then used to develop the actual scheme for congestion pricing.

CHAPTER 3 DYNAMIC CONGESTION PRICING (DEVELOPING THE DYNAMIC USER COST FUNCTION AND OPTIMAL DYNAMIC PRICING)

In the previous chapter, we discussed the concept of the static congestion pricing model (the time independent model). As discussed in that chapter, it is possible to attain an optimal system if the toll were set at the true marginal cost. In reality, however, the traffic conditions fluctuate from time to time. Thus, the marginal cost also varies with time. For the static model, the best practice is to take the average value of the traffic conditions and set the toll price to be equal to the average marginal cost value. While this may seem reasonable and adequate, there still exists opportunity to enhance this model if time were incorporated into the model.

The dynamic traffic model presents such as opportunity. As will be seen in subsequent sections of this chapter, the congestion cost of the dynamic model is expressed in a manner that accounts for such time variation of the traffic conditions. The traffic condition on the road can be represented by the length of queue on road. To control the queue, the departure rate of users from their trip origins needs to be controlled. Ideally, the dynamic model uses the variable toll as a tool to enforce such control.

This chapter incorporates the concepts of dynamic traffic modeling and variable congestion pricing. Section 3.1 introduces basic concepts of queue theory in traffic bottleneck models. Section 3.2 uses the concept of bottleneck model to derive the 1-route traffic equilibrium, and Section 3.3 converts the traffic pattern to the dynamic user cost function. Section 3.4 develops the variable toll for the dynamic 1st best pricing scheme. In Section 3.5, a new road is added to the road system, and the section derives the pattern of traffic distribution of the "2-route parallel" situation. This situation, which represents the dynamic 2nd best pricing scheme, is discussed in Section 3.6. Overall, this chapter draws on the concepts and theories presented in relevant literature (Braid 1989; Arnott, Palma et al. 1990; Arnott, Palma et al. 1990; Arnott, Palma et al. 1993; Braid 1996; Small and Verhoef 2007).

3.1 Basic Concept of the Bottleneck Traffic Model

In the deterministic bottleneck model, the entire road is viewed as a single system (Figure 3.1) and the road capacity is limited by the bottleneck. Vehicles arrive at the system/bottle neck at a rate (t) and depart at a rate (t).

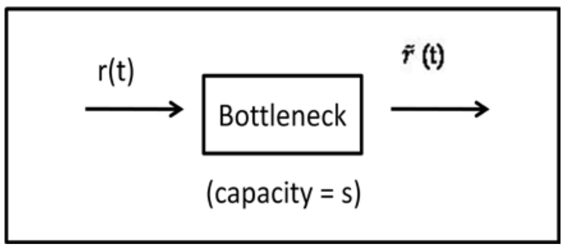

Figure 3.1 Basic Concept of the Bottleneck Traffic Model

From Figure 3.1, the bottleneck assumes to have constant capacity s (service rate of the system). If the arrival rate $r(t)$ is less than the capacity, the arrival rate $r(t)$ = the departure rate (t) and there is no queue in the system. On the contrary, if the arrival rate $r(t)$ exceeds the road capacity s, the departure rate (t) = the road capacity s. The bottleneck cannot produce service higher than its capacity s. In the latter situation, a queue builds up. Equation (3.1) shows the relationship between $r(t)$, (t), and s.

$$(t) \quad = r(t) \quad , \text{ if } r(t) \le s \, , N(t) = 0$$

$$= s \quad , \text{ if } r(t) > s \qquad \rightarrow \text{(eq. 3-1)}$$

Where; $r(t)$ = inflow capacity (arrival rate) at time t

(t) = outflow capacity of the bottleneck (departure rate) at time t

t = time a vehicle arrive at the bottleneck/system (in certain literature, the time of user departure from the trip origin, is used)

s = road/bottleneck capacity (assume constant)

$N(t)$ = number of vehicle in queue at time t, waiting for pass the bottleneck.

A graph of the traffic pattern is then plotted to represent the road system during the time period of interest (Figure 3.1). Generally, the focus is on the peak hour of traffic which starts at time t_q and ends at time $t_{q'}$ (i.e., the peak hour period is $t \quad [t_q, t_{q'}]$.) Figure 3.2 explains the traffic pattern using the cumulative vehicle arrival and the time arrival at the bottleneck. It can be noted that most papers on congestion pricing assumed that both the travel times from the trip origin (the home of the driver) to the start (queue) of the bottleneck and from the bottleneck to the destination is equal zero. These travel time amounts are constant terms in the equations. This report also follows this line of analysis.

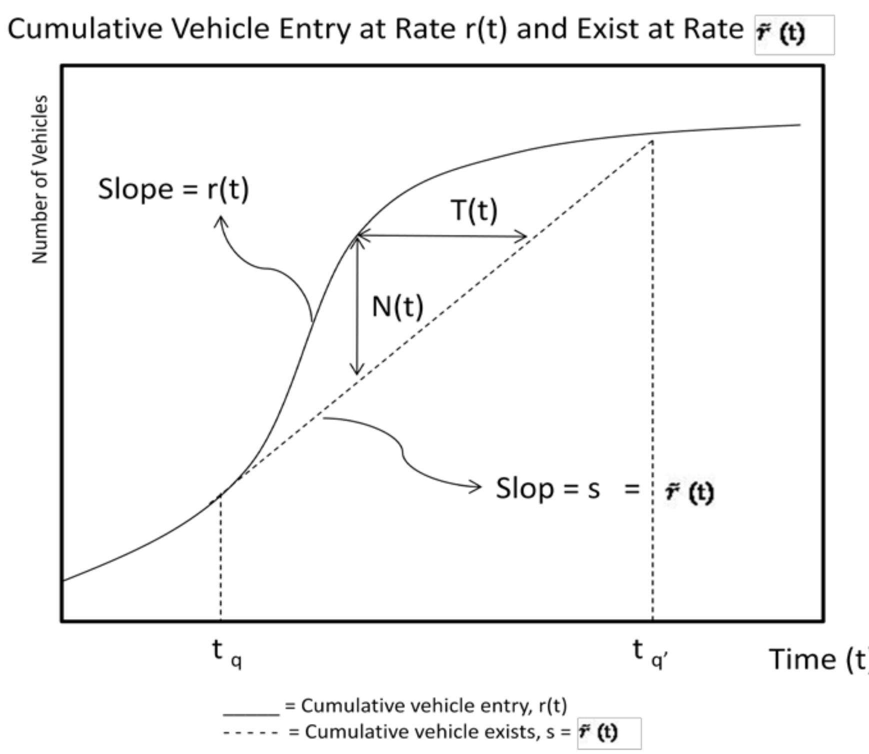

Figure 3.2: The cumulative vehicle of traffic bottleneck model

Figure 3.2 (Small and Verhoef 2007) represents the general traffic condition of the peak hour period t [t_q, $t_{q'}$] in which the amount of traffic increases beyond the road capacity. As a result, traffic starts building up at the beginning (t_q) and dissipates at the end ($t_{q'}$) of the peak hour. The two lines represent the cumulative vehicle arrival to (the bold line) and departure from (dashed line) the bottleneck. Vehicles arrive at the bottleneck at the rate $r(t$ (t) (= slope of the dash line). As discussed earlier (t) cannot exceed the capacity s. During the peak time t_q and $t_{q'}$, the arrival rate $r(t)$ > capacity s, which implies the queue starts to develop from t_q and dissipating at time $t_{q'}$. Before t_q and after $t_{q'}$ the arrival rate and the departure rate less than or equal the road capacity. Therefore, no queue exists in the system before t_q and after $t_{q'}$.

Moreover, Figure 3.2 is used to develop more important values to be used later to develop the optimal pricing toll. First, the vertical distance between the 2 lines, $r(t$ (t) curves, represents the number of road users (vehicles) in the queue at time $t = N(t)$. Second, the horizontal distance between the two lines, $r(t$ (t) curves, means the travel delay time for vehicles entering the system at time $t = T(t)$. Note that this $T(t)$ is only the time spending in queue of the bottleneck. To obtain the total travel time on a road section, the free flow travel time of the road is added to the travel delay time. The two values can be calculated from the equations below:

$N(t) =$ $= 0,$ t [$t_{q,}$ $t_{q'}$] → (eq. 3-2)

$T(t) = N(t) / s =$, t [$t_{q,}$ $t_{q'}$] → (eq. 3-3)

Where; $N(t)$ = the number of vehicles in queue at time t. (Note that: this is derived from $N(t)' = r(t) -$ (t)).

$T(t)$ = time delay of vehicles entering the system at time t (only time spent in the queue).

t = arrival time of the vehicle (at the queue), and t [$t_{q,}$ $t_{q'}$]

s = the road capacity, $r(t)$ = the arrival rate of vehicle

t_q – the first time $r(t) = s$; that is, the beginning of the peak hour

$t_{q'}$ – the end of the peak hour.

From Equations 3-2 and 3-3, (i) at time t_q the queue just starts to build up, which means no queue has developed yet, $N(t_q) = 0$, (ii) at time $t_{q'}$ the entire queue dissipates at the end of the peak hour, $N(t_{q'}) = 0$. From Figure 3.2, these two points show that there is no gap between the *r*(*t* (*t*) curves at the time t_q and $t_{q'}$.

3.2 The Traffic Equilibrium of Bottleneck Model (1-route scenario)

This section develops the traffic equilibrium pattern. First, the concept of user cost function in dynamic traffic model is introduced (Section 3.2.1) followed by the use of the user cost function to develop the traffic equilibrium in a dynamic setting. These results are used to derive the variable toll amounts in subsequent parts of the report.

3.2.1 The Dynamic User Cost Function

An advantage of the dynamic model is that it can consider the schedule delay cost of users. As previously discussed, the dynamic pricing adjusts the variable toll to force road users leave their trip origins (often, their homes) and enter the road system at optimal level. The toll does not control the road queue directly but rather influences the user to select a time to make their trips, on the basis of the reschedule delay cost and queue delay cost. Greater detail is provided in subsequent parts of this chapter.

The development of the cost function for the dynamic model follows almost the same line of thinking as that for the static model; however, for the dynamic model, another term $D(t)$, the schedule delay cost, is added. The schedule delay cost can be interpreted as the amount of money that the user is willing to pay to leave home earlier or later than their desired time in order to avoid the traffic queue. To build the cost function, it is assumed, from this point onward, that all road users prefer to leave home at time t_d and they make trip timing decisions by minimizing their individual cost only. These are key assumptions for the model development. In the Appendix, it is shown how to carry out the analysis for the more general case where trip makers have different desired times of departure from their trip origins (their homes). The short-run cost function in the dynamic bottleneck model can be expressed as follows:

$c(t) = c_0 + \alpha T(t) + D(t)$ → (eq.3-4)

and $D(t) = \beta\,(t_d - t - T(t))$, if $t + T(t) < t_d$ (early departure from home)

$= \gamma\,(t + T(t) - t_d)$, otherwise (late departure from home). → (eq. 3-5)

Where; $c(t)$ = user cost associated with a section of road at time t

$D(t)$ = schedule delay cost

α, β, γ = unit value of travel time for normal, early, and late departures, respectively

c_0 = the fixed part of travel cost, such as VOC and fuel cost

$T(t)$ = amount of time taken to use the section of the congested road at time t (i.e., time in queue $T^v(t)$ + free flow travel time)

($T^v(t)$ is obtained from equation (3-3)

t = departure time from trip origin (home), assumed to be equal to the time of arrival at the bottleneck

t_d = desired time to arrive at trip destination (assumed to be the work location).

From equation 3-4, it is observed that road users pay a travel cost in order to make a trip. This cost comprises three parts; a fixed cost = c_0, the cost of time spending in queue = $\alpha T(t)$ and the cost of time in changing their desired departure time from home = $D(t)$. The first two terms are similar to those of the static model ($c_0 + \alpha T(t)$). The last term, the schedule delay cost $D(t)$, is unique to the dynamic model. That is, the value of schedule delay cost can be captured by the dynamic model. Road users will seek to minimize the cost of making a trip by trading off between the time spent in the queue bottleneck and the time delay or hastening due to early or late departure from home.

Generally, if the road has infinite capacity and thus, no congestion, all trip makers will be expected to depart from their trip origins at their desired times. In this situation, they minimize the user cost (the schedule delay cost is assigned as zero) and their delay cost is also zero due to absence of congestion. However, this is not the case in reality. Due to limited road capacity, a certain number of road users need to leave their trip origins earlier or later than they would have preferred, in order to avoid the queue caused by congestion. For this realistic situation, drivers seek to minimize their user cost by trading off between cost of queuing delay $\alpha T(t)$ and the schedule delay cost $D(t)$. In the next section, the concept is further clarified through the derivation of the equilibrium travel pattern. This pattern is based on the assumption that every road user undertakes the trip only by minimizing their individual user cost.

3.2.2 Traffic Equilibrium Conditions

This section presents the traffic equilibrium of the traffic bottleneck model without any toll. The model is based on the following assumptions:

- The system is a single road section (the road bottleneck). Road users enter the system at time t and leave at time t' (where $t' = t + T(t)$, and $T(t)$ = time spent in the system).
- The demand is N vehicles that need to use the system during the peak hour t [$_q$, $t_{q'}$]
- All vehicles have the same desired time of departure from home t_d and time of leaving the queue, t* (Note that $t^* = t_d + T(t_d)$ where $T(t_d)$ = time spent in the queue if the road user leaves home at time t_d). Note that, the home departure time t might be considered in a manner similar to the time of leaving the queue, t'. A reference time is what needs to be identified. From this point on, the report uses t' as the main reference time.
- Road users seek to minimize their individual user cost by adjust their departure times from their trip origins (their homes). The system continues until it reaches the equilibrium.
- Without loss of generality, it can be assumed that the time of departure from the trip origins is the same as the time of arrival at the queue; and the time of leaving the system is the same as that of arrival at the destination (work location).

The full mathematical proof for traffic equilibrium is provided in the Appendix.

The key premise underlying the traffic equilibrium is that road users seek to adjust their origin-departure times to minimize their user cost $c(t')$. The system continues until everyone in the system reaches the same user cost. At this point, the system is used at the full capacity for the entire peak hour. Figure 3.3 (adapted from Small and Verhoef, 2007) illustrates the traffic pattern under equilibrium conditions of the system.

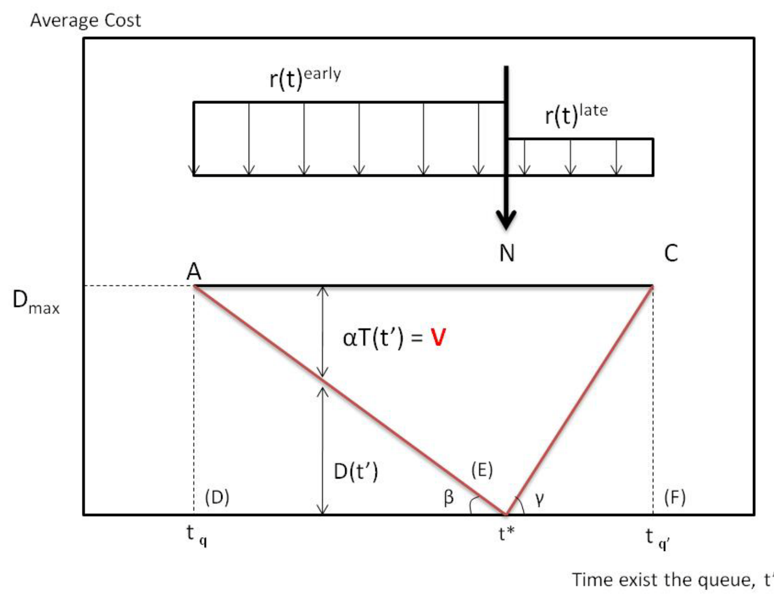

Figure 3.3: Bottleneck model congestion cost for basic same departure times of users

Explanations for Figure 3.3 are as follows:

- The top part of Figure 3.3 shows the traffic flow pattern that arrives at a bottleneck. As stated above, all the *N* vehicles during the peak hour desire to leave the system or to arrive at workplace at time t* (see bold arrow). However, due to bottleneck capacity, drivers minimize their own cost of travel by trading off between queues on road and trip rescheduling. After the system keep re-adjusting to reach the equilibrium, the bold arrow spreads out into two groups: road users who decide to leave home early to avoid queue and ones who choose to leave home late to avoid queue. These two groups of road users produce the rate that depart from home early and late = $r(t)^{early}$ and $r(t)^{late}$, respectively. The two departure rates can be calculated as follows:

  $r(t')^{early} =$ s+ (—— (> s), and $r(t')^{late} =$ s - (—— (< s) → (eq. 3-6)

  where; s = road capacity

α, β, γ = unit value of travel time at normal, early, and late departures, respectively. (The full derivation of these results is provided in the Appendix.)

- The line AEC represents the schedule delay cost $D(t')$. Road users choose the departure time that minimizes their individual cost.
- The vertical line between any point AC and the corresponding point (vertically below) on AE or EC represents the travel delay cost (or the cost due to choosing to join the queue) $\alpha T(t')$.
- The line AC is the total congestion cost $c_g = \alpha T(t') + D(t')$. This cost varies with the traffic demand N. Here, Wardrop's theorem holds: every road user pays the same price at equilibrium conditions.
- As stated above, road users attempt to minimize their individual total congestion cost by choosing the time of departure from their trip origins (their homes), t (or the time of leaving queue t'.) The greater the deviation from the desired departure time t_d (or t^*), the greater the schedule delay cost, $D(t)$. On the contrary, the queue delay will decrease as one moves away from the desired departure time t*, a reflection of the tradeoffs that occur until the system equilibrium is reached.
- If a road user departs from the queue at the beginning of peak hour $t_{q'}$ and at the end of peak hour t_q, then that user will have no queue delay on the road ($\alpha T(t')$ =0) but will pay the highest schedule delay cost $D(t') = D_{max}$. If the road user departs at their desired time t*, then the user faces the highest travel delay cost $\alpha T(t')$, but will not need to reschedule their trip ($D(t^*)=0$).
- Moreover, the slope of the line AE or EC is the unit of reschedule delay cost, which is β (for early departures from trip origins), and γ (for late departures from trip origins).
- In sum, every road user in the system pays the same total congestion price c_g and the queue starts at t_q and end at $t_{q'}$.

The results which are consistent with the concepts in Small and Verhoef (2007) are presented below (the full proof is provided in the Appendix). It may be noted that the superscript "e" means the value at equilibrium without pricing. In the next section, the values with the superscript "o" means the value at optimal first-best pricing.

$_g^e = \delta -$ $=$ p^e → (eq. 3-7)

$t_q = t^* -$ —— . – → (eq. 3-8)

$t_{q'} = t^* +$ —— . – → (eq. 3-9)

where;

$_g^e$ = user congestion cost = generalized price of making a trip p^e (without toll implemented)

α, β, γ = unit value of travel time, early departure, and late departure, respectively

N= total number of users during the peak hour

s= road capacity

t = departure time from home/ or arrive at the bottleneck

*t** = desired time to leave the system/ queue

t_q – the beginning of peak hour.

$t_{q'}$ – the end of peak hour.

δ = βγ/ (β+γ) or = βσ

σ = ——.

It may be noted from equation 3.7 that the term congestion cost, $_g^e$, does not yet include the vehicle operating cost. From the user cost function (Eqn 3.4), the user cost is $c(t) = c_0 + \alpha T(t) + D(t)$; the congestion cost is $_g^e = \alpha T(t) + D(t)$.

Finally, to solve for the traffic equilibrium, $_g^e$ (from equation 3-7) can be substituted in equation 3-4 to obtain full user cost function ($c(t) = c_0 +\ _g^e$). Then the user cost is equated to the demand function and the corresponding number of vehicles in the system is determined. The rationale for doing this is that technically, the cost function can be viewed as the supply function (the market equilibrium is the intersection point of supply and demand functions).

3.3 Dynamic First-best Pricing Scheme

In a previous section, the user cost function was developed using dynamic congestion analysis and this led to the derivation of the traffic equilibrium condition. This section presents the variable toll scheme that promotes the optimal social surplus. Still, we are considering the case here the system is a single road section.

To derive the optimal variable toll, reference could be made to the static pricing. In Chapter 2, it was shown that at optimality, the marginal cost and the marginal benefit are equal. This result is proven without any restriction on congestion cost. That is, this condition still holds for the dynamic pricing analysis. Actually, at optimality MC = MB, irrespective of the similarity of the cost and demand functions.

The dynamic first-best pricing is based on the following assumptions and concepts:

- It is sought to maximize social welfare. Therefore, it is sought to identify the optimal toll that is equal to the marginal externality cost (marginal cost – average cost).

- The time that is spent in the queue is considered a "deadweight loss". The toll to be collected is equal to this amount.

- The variable toll is priced as follows: "*V*" = travel delay cost $\alpha T(t')$, as seen in Figure 3.4. The variable toll V starts from 0 at the beginning of peak hour t_q, increases to a maximum at t^*, and falls back to 0 at the end of peak hour $t_{q'}$. The vertical bold arrow in the triangle represents the variable toll *V* at any time *t*' during the peak hours.

- This pricing scheme makes no road user worse off! The toll is priced such that instead of spending time in queue, road users will prefer to spend the same amount of time at home or at the office by leaving the trip origins (homes) later or earlier than the desired time t*.

- The variables $r(t)^{early}$ and $r(t)^{late}$ in equations 3-6 do not hold in this case. The $r(t)^{early} = r(t)^{late} = s$ for the entire peak hours. Road users depart from their trip origins at the rate of bottleneck capacity and no road user faces a queue. The road system is used exactly at full capacity: it is not overused and there is no queue. The variable toll V influences road user's decisions to depart from home a little bit later comparing to the departure time associated with non-pricing equilibrium. This result may be compared with the explanation for equation 3-6 and Figure 3.4.

Figure 3.4 illustrates the dynamic first-best pricing scheme.

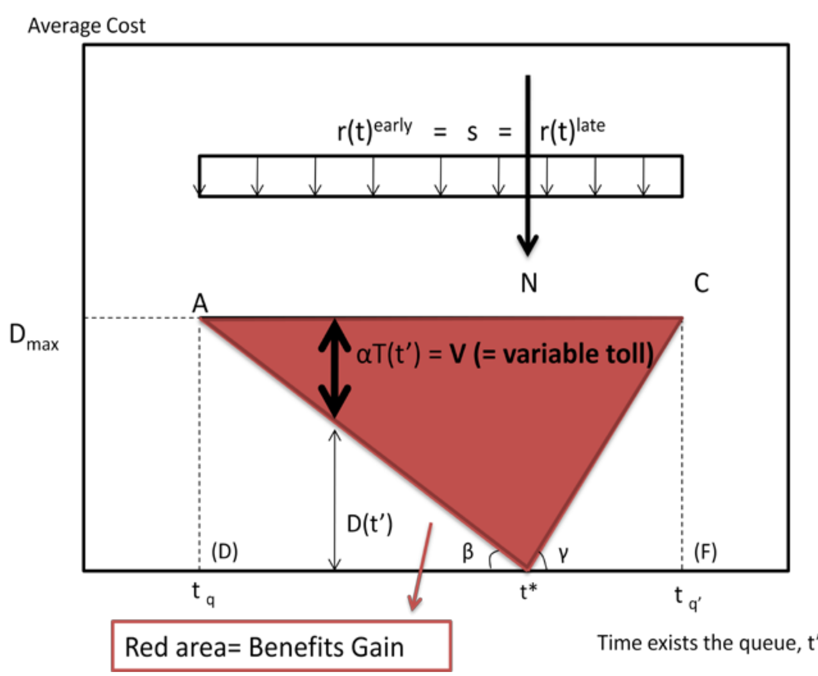

Figure 3.4: The dynamic first-best pricing scheme.

- Ideally, the deadweight loss is transferred from the on-road queue into toll revenue and road users still pay the same user cost. However, the congestion cost is reduced by half. Instead of paying travel time cost $\alpha T(t')$ by spending time in the bottleneck queue, road users pay the variable toll V instead and face no road queue. Then, no one is worse off and the agency gains toll revenue! Also, the departure rate from queue or arrival rate at work place is still the same.

- In Figure 3.4, the shaded triangle represents is the benefit gain. Without variable toll, this triangle is the loss that drivers pay by spending time in the queue. Thus, the system is overused if the variable toll is not imposed. After the optimal toll is implemented, this amount of money becomes agency revenue. Therefore, the triangle represents the benefits from the dynamic first-best pricing implementation.

The following bullets explain why this situation is optimal:

- $r(t) = s$ for the entire peak hour is optimal. Because if $r(t)$ falls below S, the peak hour could be compressed to become smaller and the schedule delay reduced. The cost for road users who first exit the system at t_q will need to be equal to the cost for those who last exit the system at $t_{q'}$. Otherwise, road users will simply reduce the cost by behaving in a manner that leads to a shift in the peak hour.

- Wardrop's principle holds; this means that every road user faces the same generalized price.

Thus, the first-best variable toll can be written formally as follows:

$$
\begin{aligned}
V(t') &= 0 && \text{, if } t' < t_q \\
&= \beta\,(t' - t_q) = \delta - - \beta\,(t^* - t') && \text{, if } t_q \le t' \le t^* \\
&= \gamma\,(t' - t_q) = \delta - - \gamma\,(t^* - t') && \text{, if } t^* \le t' \le t_{q'} \\
&= 0 && \text{, } t' > t_{q'} \qquad \rightarrow \text{(eq. 3-10)}
\end{aligned}
$$

Also, every road user still faces the same generalized price (as no toll is implemented):

$$p^o = \delta\, — \qquad \rightarrow \text{(eq. 3-11)}$$

However, the congestion cost reduces by half due to no queue on road:

$$_g{}^o = 0.5\ \delta - \qquad \rightarrow \text{(eq. 3-12)}$$

Where; $_{g}^{o}$ = user congestion cost after implementing variable toll

α, β, γ = unit value of travel time, early departure, and late departure, respectively

N = total number of users during the peak hour

s = road capacity

t' = departure time from queue/ or arrive at the destination (i.e., the workplace)

t^* = desired time to leave the system/ queue

t_q – the beginning of peak hour.

$t_{q'}$ – the end of peak hour.

$\delta = \beta\gamma / (\beta+\gamma) = \beta\sigma$

σ = ——.

It may be noted that all users pay the same generalized price because the schedule delay cost, $D(t) = 0$, is offset exactly by the variable toll, V. This is why the congestion cost in equation 3-12 reduces by one half of the value derived previously (equation 3-7).

In sum, no road user is worse off after the agency imposes the dynamic first-best toll. The users pay the toll but the toll is exactly offset by the cost of queuing in the bottleneck which is total deadweight loss. Ideally, this deadweight loss is transferred into agency revenue thus serving as a benefit. This is a major departure from the static model that cannot consider the schedule delay cost.

Therefore, the individual consumer surplus remains the same after implementing the first-best dynamic toll. No one is worse off. If well articulated and communicated to the general public, this situation can help the agency gain public acceptance of the tolling scheme. It can be noted that the social surplus (SS) increases in a manner that is equal as that of the toll revenue.

3.4 Traffic Equilibrium Conditions for "2-routes parallel" (without toll)

The traffic equilibrium of 2-routes parallel (without toll) is analyzed herein on the basis of concepts provided by Palma and Lindsey (2000). From Section 3.3, the 1st best pricing scheme for the dynamic traffic model was obtained. However, in reality, if there is more than one route connecting the origin and destination, then the static 1st best (Section 3.3) is not necessarily the optimal. The question then arises as to what should be done to promote the social optimal of the system.

This section discusses how to model traffic that needs to go from an origin X to a destination Y when having a choice between two parallel routes. No toll is imposed in this section. After the equilibrium pattern of traffic is obtained, the amount of toll is derived in the next section (Section 3.5).

A suitable preliminary consideration in this analysis is to establish how road users make their trip decisions. One way to model this decision process is to assume that they face three choices to complete their trip: i) whether to drive, ii) which route to take, and iii) when to depart from their homes. From the planning perspective, there is a need to model these steps and thus to establish the equilibrium traffic pattern. The steps need to be modeled in reverse order (i.e., model the step iii first, and then "back-calculate" to solve iii) (Palma and Lindsey, 2000).

The scope of the model and assumptions are first defined as follows:

- There are N trips that need to get from X to Y during a peak period t $[t_q, t_{q'}]$. N is not necessarily fixed but can vary according to the demand function. All N vehicles prefer to arrive at destination at time t^* but due to limited capacity, the traffic spread out through the peak hour (see Figure 3.4).

- Two routes are available, route A and route B, thus R {A, B}. The number of vehicles traveling on route R is N^R, that is, N^A vehicles choose to travel on route A, and N^B vehicles choose to use route B.

- Route R has a capacity s^R, and free-flow travel time ^{R} as R {A, B}.

- It is assumed that the cost of travel time, reschedule delay, and toll have equal weights in the user cost function.

- It is assumed that the schedule delay cost linearly increases with reschedule time. In a section that follows shortly, it will be seen how this assumption is implemented in building the cost function.

- It is assumed that all road users are homogenous in their willingness to pay for a trip. Each trip has a unit travel time value, α; a unit early-reschedule cost, β; and a unit late-reschedule cost, γ.

The purpose is to answer the following questions: how many rod users will undertake a trip; how will the traffic be distributed between the two routes; and how long will the peak period last? The basis for developing the traffic pattern in equilibrium of 2-route parallel, are provided in the bullets below (the full mathematical proof is provided in Appendix A).

- First, the user cost functions of vehicles entering route R {A, B} at time t' $[t_q, t_{q'}] = c^R(N^R)$ at time t', are established. To solve for the user cost on route R, Wardrop's theorem, which states that all road users travelling on route R during peak hour face the same user cost, is used. That is, no matter what time during the peak hour, road users on route R have to pay the same trip cost. Upon this basis, the cost function for each route can be derived. The result is as follows:

$$c^R(N^R) = \alpha\ {}^R + (\text{——})\ N^R/S^R + \tau^R \qquad \rightarrow \text{(eq. 3-13)}$$

(Note that, $\tau^R = 0$ in this section because at this point of the analysis, the toll is not yet collected).

where;

$c^R(N^R)$ = the user cost function of vehicles using route R {A, B} at time

t' $[t_q, t_{q'}]$

^{R} = free flow travel time on route R {A, B}

α, β, γ = unit value of travel time, early departure, and late departure, respectively

N^R = total number of users on route R during the peak hour

S^R = road capacity of route R

$\tau^R = 0$ = the amount of toll to be collected on route R (it is zero in this section.)

- Second, the cost function of each route $c^A(N^A)$ and $c^B(N^B)$ (Berenbrink and Schulte) from the first step (eq. 3-13), is thus obtained as a function of N^A and N^B, respectively. To solve for N^A and N^B, it is considered that the trip cost on both route are equal under equilibrium conditions; otherwise, traffic diverts to the route with lower cost until equilibrium is reached. It may be recalled that $N^A + N^B = N$, where N = total demand needed to travel from X to Y.

  $c^A(N^A) = c^B(N^A) = c(N)$ → (eq. 3-14)

  $N^A + N^B = N$ → (eq. 3-15)

  Where; $c(N)$ = cost of making a trip from X to Y

  N = total number of vehicles travelling from X to Y

  N^A, N^B = the number of vehicles traveling on routes A and B, respectively.

- Third, at system equilibrium, the demand curve intersects with the supply curve. That is, the generalized price of making a trip (demand curve) is equal to the user cost.

  $p(N) = c(N)$ → (eq. 3-16)

  where:

  $p(N)$ = an inverse demand function of trip from X to Y that take either

  route A or B.

Solving equations (3-13) to (3-16) together yields all the parameters of the 2-route parallel traffic equilibrium. This section only briefly describes the pattern of traffic equilibrium of the “2-routes parallel” scenario that is needed to derive the toll amount in the next section. Additional explanation is provided in the Appendix.

3.5 Dynamic Second-best Pricing Scheme (2-route parallel)

At this point, the report has established the traffic pattern of the two routes parallel without toll (Section 3.4). In this section, toll is introduced to one or both of these routes and the resulting change is calculated. It is assumed that route A is priced and route B is left free.

For the second-best pricing, the variable toll V^A on route A is equal to the travel delay cost. Similarly, the variable toll on route A, V^A, starts from zero at time $t_{q,}$ increases to a maximum at t* and falls back to zero at the end of peak hour $t_{q'}$. However, due to traffic diversion between the 2 routes, the term τ^A flat toll (that is, the additional charge to the original variable toll V^A on the route A, is added. This amount, τ^A, is set to encourage the traffic distribution between route A and B such that social welfare is maximized. Note that a negative value of τ^A is possible and represents the case where the agency subsidizes the user cost.

The same methodology as described in Section 3.4 is applied. However, in Equation 3-13, the toll τ^A is allowed to have a non-zero value. The question is that there exists one more unknown variable (τ_R) which must be solved. The three steps previously introduced in Section 3.4 are inadequate to do this (in the previous section, it was assumed that τ^A is zero and the traffic pattern of 2-route equilibrium was solved).

To solve for the flat toll τ^A, the social surplus optimization problem is set up. That is, τ^A is adjusted to maximize the social surplus. The variable toll is similar to the 1-best toll whose charge varies but is equal to the travel delay cost.

The maximization of the social surplus can be expressed as follows:

$$\text{Max } SS = - c^A(N^A)\, N^A - c^B\, N^B + I^A\tau^A\, N^A + I^B\tau^B\, N^B + I^A V^A + I^B V^B$$

→(eq. 3-17)

Where; SS = total social surplus = CS + Revenue

CS = total consumer surplus = $- c^A(N^A)\, N^A - c^B\, N^B$

Revenue = total toll revenue collected during a peak hour = $\tau^A\, N^A + \tau^B\, N^B + I^A V^A + I^B V^B$

I^R = indicator variable = 1 if route R is tolled, 0 otherwise, for R {A, B}

V^R = variable toll on route R, for R {A, B}

$c^R(N^R)$ = cost function of users who choose route R, as R {A, B}, defined as eqn 3.14.

τ^R = flat toll on route R that is collected additional to variable toll V^R

Note: $V^B = \tau^B = 0$ in this setting but are mentioned herein for purposes of further reference within a more flexible setting.

Solving equation 3-17, the first-order condition is used by taking the 1st derivative and setting it equal to zero. Then the function is rearranged to yield the following result:

$\tau^A = C^A_N N^A + [|P_N|/ (C^B_N + |P_N|)].N^A - I^A V^A_N$ → (eq. 3-18)

(τ^B is the same formula as one could simply interchange the A and B subscripts).

where; c^R_N = the 1st derivative of c^R with respect to N, for R {A, B}

V^A_N = the 1st derivative of V^R with respect to N, for R {A, B}

P_N = the 1st derivative of the inverse demand function p(N) with respect to N.

Note: In equation 3-18, to implement 1-route pricing (the other is free) on route A, we simply substitute $I^A = 1$ and $\tau^B = I^B = 0$. If both routes are tolled, then $I^A = I^B = 1$ and equation 3-18 reduces to first-best pricing with the road capacity = sum of capacity of route A and B.

Here is a flat toll τ^A (and τ^B which is zero here) from equation 3-18. To obtain all the results and traffic conditions, equations (3-13) to (3-16) from Section 3.4 and equation (3-18) are solved.

It may be noted that equation 3-18 can also be used to carry out analysis for the static case. By dropping the term "variable toll V^A_N", this equation becomes exactly the same as equation 2-18 that was used for static 2nd best pricing. Reference may be made to Section 2.4 for comparison to the static case. Greater detail is provided in Chapter 5.

To derive the benefit gain, the difference of social surplus (SS) between the base case (2-route parallel without toll) and the 2nd –best pricing scheme (tolling one of 2-route parallel) can be calculated. All parameters can be calculated as previously discussed in Sections 3.4 and 3.5 (solving equations 3-13 to 3-16 and 3-18). The results from both scenarios are substituted into equation 3-17 to obtain the social surplus for each of the two scenarios. The benefit gain due to implementing the dynamic 2nd–best pricing scheme is the difference of these two social surplus values.

CHAPTER 4 APPLICATION OF THE MODELS

This chapter demonstrates the application of the pricing models at the Interstate 69 highway section between Fishers and the I-465 ramp at Indianapolis. Section 4.1 discusses the parameters and assumptions of the model. Also, the actual cost and the demand functions are also derived using real data. Section 4.2 describes the complete steps of optimal toll calculation and traffic equilibrium. Two scenarios are described, and under each scenario, two situations are presented. Sections 4.2.1 to 4.2.3 discuss the 1-route situations, and Sections 4.2.4 to 4.2.6 discuss the 2-route situations.

4.1 Problem Statement and Data Description

The data source used for the case study is Davis III (2008).

4.1.1 Problem statement and purpose of analysis

At the current time, the I-69 highway located on the north-east of the Indianapolis between Fishers and Interstate 465 ramp has been facing serious congestion problems during peak hours. According to the data, during the morning and evening peak hours from April 2 to May 1, 2008, the travel speed dropped from the free flow speed of 62 mph down to 46 mph, on average (Davis III 2008). To mitigate the problem, this chapter of report designs and evaluates a number of congestion pricing alternatives. This is done for both the static and dynamic settings. The analysis is presented using six scenarios (and two scenarios in the Appendix): three cases of 1-route analyses and the other three cases of 2-route analyses as shown in the next section (Section 4.2). The main results of analysis include the benefits of congestion pricing, the change in consumer surplus, the before-and-after traffic condition and the optimal amount of toll.

The motivation for presenting the case study is to show how the theories and equations derived in previous chapters, can be applied in real life to ascertain the feasibility of congestion pricing at a candidate corridor. However, in this report, the demand and the cost functions are roughly estimated from real but rather limited data. A number of assumptions are made in order to develop the demand and cost functions fully. Any future efforts geared towards an analysis of congestion pricing at that stretch of highway should be preceded by a refinement of these assumptions by acquisition of more up-to-date and accurate data on cost and demand functions for the highway section.

4.1.2 Road characteristics

The stretch of interest is the I-69 highway located north-east of Indianapolis. It links downtown Indianapolis to Hamilton County. Six miles of this section (from mile marker 0 to 6) experiences very heavy traffic. This road section has six lanes (three lanes in each direction – North bound and South bound) from MM1-6, and has 8 lanes from MM 0-1. Traffic data were collected for 22 weekdays, April 2 to May 1, 2008. The traffic data sources were four traffic count stations located at mile-markers 0.5, 2.1, 3.7 and 5.4. From these four stations, the traffic data from mile 2.1 shows the most extreme traffic pattern, suggesting the existence of a traffic bottleneck at this section during peak hours. Therefore, the traffic data from the count station at mile 2.1 was used to build the traffic model. The morning peak hour is on the South bound direction of the highway (heading to downtown Indianapolis) and the evening peak hour is on the North bound direction. The morning peak hour occurs at approximately 6.00-9.00 AM and the evening peak, 15.00- 19.00. The following preferable times of exiting the queue in morning and evening t* are assumed to match the current traffic pattern.

- It is also assumed that road users prefer to leave the bottleneck in the morning at time, t* = 8.0 (or about 8:00AM)
- For purposes of this report, it is assumed that road users prefer to leave the bottleneck in the afternoon at time, t* = 18.3 (or about 18:2GMT or 6:20PM)

To implement the priced lane, it is assumed that the agency will construct a 6-mile, 1-lane roadway in the median of the existing I-69 highway. The new lane will be constructed from MM0 to MM6. The new lane is open to the SB in the morning and to the NB in the evening. That is, for the morning peak, the analysis is carried out for the SB with 3 old lanes and new 1 additional lane located in the median, and for the evening peak, the analysis is carried out for the NB with 3 old lanes and new 1 additional lane located in the median. From this point forward, route A refers to the new roadway (1-lanes) and route B refers the old roadway (6-lane with 3-lane on the North bound and 3-lane on the South bound).

- Capacity of route A, S^A = 1600 veh/hr (1 lane with capacity 1600 vph. per lane)
- Capacity of route B, S^B = 4800 veh/hr (3 lanes with capacity 1600 vph. per lane)
- Free-flow travel time on route A, ^{A} = 10/60 hour.
- Free-flow travel time on route B, ^{B} = 10/60 hour.

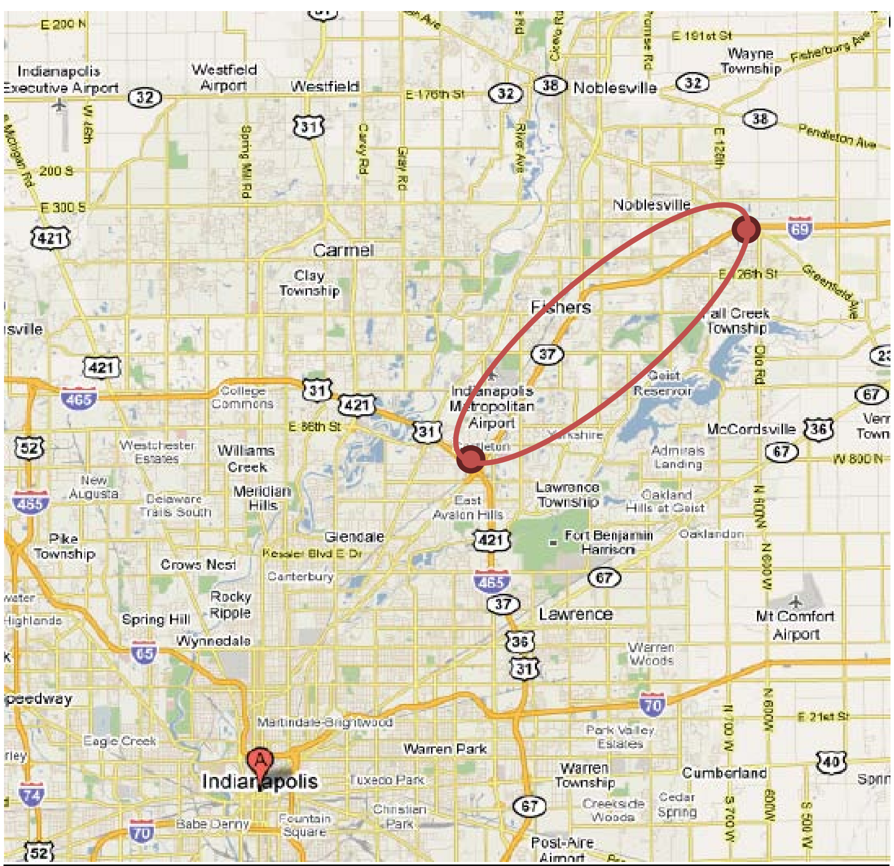

Figure 4.1: I-69 Road Section (source: (Google-Maps 2010)

4.1.3 Cost Functions

Assumptions and parameters of the cost functions. The assumptions are:

- Travel time value, α = \$5/hour
- Value of time for early reschedule delay, β = \$ 2.5/ hour
- Value of time for late reschedule delay, γ = \$9.75/ hour

The assumption of travel time value α is adopted from the willingness-to-pay survey carried out by Davis III (2008). It is assumed that the values of the reschedule delay cost β and γ are in the same ratio of provided in the literature (Small 1982).

- The vehicle operating cost (a fixed part of the user cost associated with a trip) c_0 = \$2/ (6miles)

The vehicle operation cost is adopted from the literature (Small and Verhoef 2007). The value includes vehicle operating, vehicle capital, roadway, and parking cost.

The dynamic user cost function is then developed and it is shown that the same user cost function can be also use to analyze the static setting.

The Dynamic user cost function: From above parameters, the development of dynamic user cost function is rather straightforward. All the input parameters are substituted into equations 3-4 and 3-7 (see Chapter 3).

For the sake of continuity, equations 3-4 and 3-7 are repeated herein:

Equation 3-4: $c(t) = c_0 + \alpha T(t) + D(t)$, where $\alpha T(t) + D(t)$ = congestion cost g^e

From equation 3-7, $g^e = \delta -$ =(——) N/s };.

Therefore, the user cost function for users on route A and B are as follows:

$c^A(N^A) = c_o + \alpha\ ^A + (\text{——})\ N^A/S^A + \tau^A = 2.83 + (1.244\text{x } 10^{-3})\ N^A + \tau^A$, if $N^A > S^A$

$= c_o + \alpha\ ^A = 2.83$, if $N^A \leq S^A$ →(eq. 4-1)

$c^B \;= c_o + \alpha \;\; ^B + (\text{——})\, N^B/S^B + \tau^B \quad = 2.83 + (4.145\text{x } 10^{-4})\, N^B + \tau^B \quad , \text{if } N^B > S^B$

$\qquad = c_o + \alpha \;\; ^B \qquad = 2.83 \;, \text{if } N^B \leq S^B \qquad \rightarrow$(eq. 4-2)

Where; c(N) = average user cost as a function of the number of vehicle N on that route

τ = flat toll on a route.

The dynamic user cost function can be illustrated as Figure 4.2.

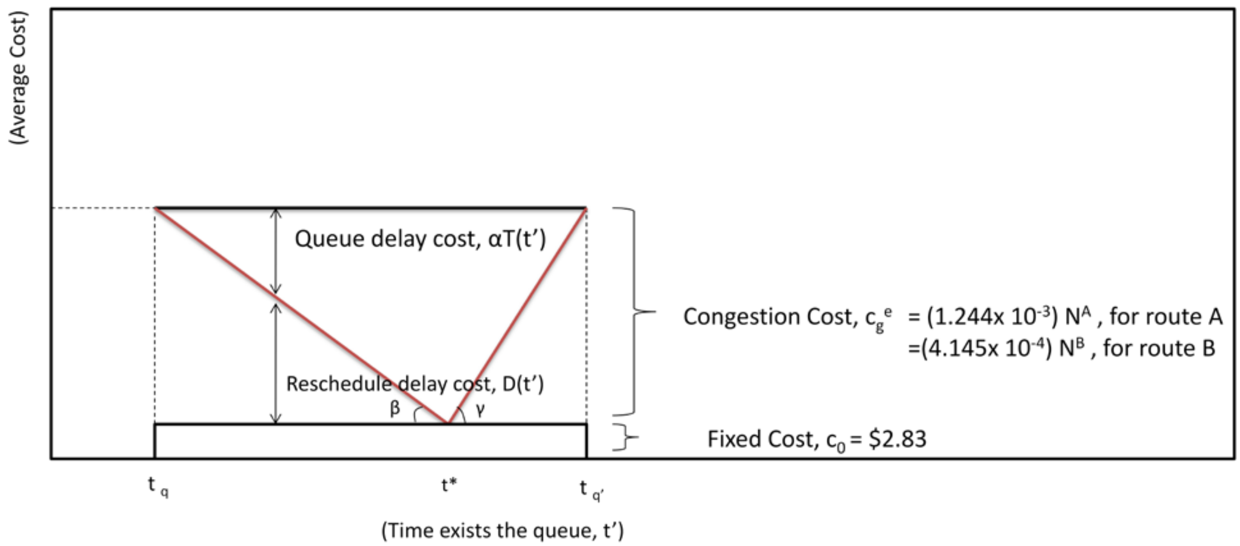

Figure 4.2: The dynamic user cost function for the case study

<u>The Static user cost function:</u> It is now shown that equations 4-1 and 4-2 can be also used in the static congestion pricing. The equations 4-1 and 4-2 of dynamic user cost functions are actually the time-averaging linear-piecewise model in the point of view of static traffic model. If the level of traffic is less than capacity *s*, the user cost to use this road is = c_o = \$ 2.83. When the traffic level exceeds capacity, the user cost to use this road is = $c_0 + c_g$ (see equation 2-1 and 2-3 in Chapter 2).

For the sake of continuity, equations 2-1 and 2-2 are repeated below:

From equation 2-1, $c = c_0 + c_g + \tau$

From equation 2-3, c = = $c_0 + \alpha.\ a.(N/s) + \tau$

Comparing equation 2-3 with the dynamic cost function above, the term $(\alpha)(a).1/s$ of equation 2-3 is observed to be the term (——) $1/s$ of dynamic cost function. That is, equations 4-1 and 4-2 can be used to calculate the static congestion price amount. Figure 4.3 shows the static cost functions, i.e., equations 4-1 and 4-2, from the static setting viewpoint.

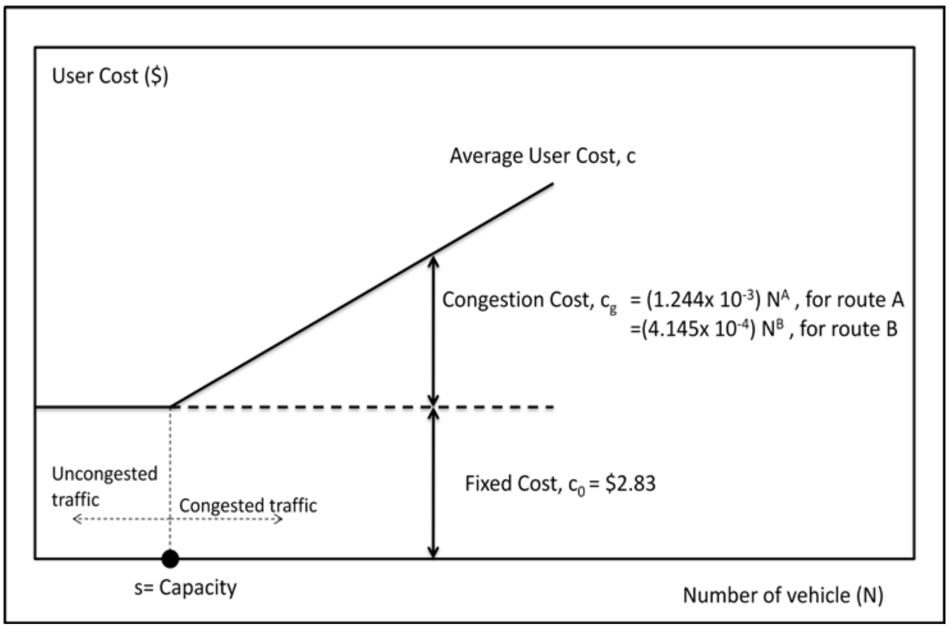

Figure 4.3: The static user cost function for the case study

It is important to note that this <u>does not mean</u> that the static traffic model can handle the reschedule delay cost. It must be emphasized that the static traffic model is a time- independent model. However, because the analysis herein uses the <u>basic bottleneck model</u>, it is therein assumed that all the road users have the same desired departure time t*. <u>As a result, all road users face the same user cost during the peak hour; this matches the assumption of time-averaging static model</u>. For this reason the same user cost can be used in both static and dynamic settings.

4.1.4 The Demand function

<u>Assumptions and parameters of demand functions</u>:

- The demand function is assumed to have constant price elasticity. The Cobb Douglas function is adopted. The inverse demand function is:
  $p(N) = p_o N^{(-1/\varepsilon)}$
  where; p_o = a constant parameter
  ε = demand elasticity with respect to trip price.
- For the both evening and morning peak hours, it is assumed that $\varepsilon = 1$.
- For the evening peak hour p_o = 221,513; for the morning peak hour p_o = 124,553. Both p_o's are assumed to match the current data associated with the peak hour.

By using parameters and assumptions above, the demand functions are determined as follows.

Demand functional form → $p(N) = p_o N^{(-1/\varepsilon)}$

For the morning peak hour: $p(N) = 124{,}553/ N$ → (eq. 4-3)

For the evening peak hour: $p(N) = 221{,}513/ N$ → (eq. 4-4)

The demand functions (equation 4-3 and 4-4) are illustrated in Figure 4.4.

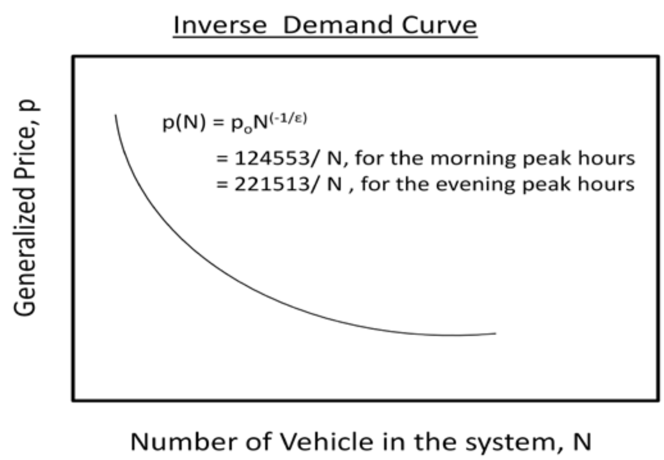

Figure 4.4: The (inverse) demand curve

4.2 Model Calculations (6 pricing scenarios)

This part of the report shows the calculations of traffic equilibrium and optimal pricing schemes. Six pricing scenarios are presented. Sections 4.2.1 to 4.2.3 discuss the 1-route situations, and Sections 4.2.4 to 4.2.6 discuss the 2-route situations. Also, two additional cases of 2-route parallel are discussed in the Appendix.

4.2.1 Traffic equilibrium conditions for 1 route no toll (Do nothing case)

Note that, route B is the existing road and the road A is a new constructed one. As stated previously, all parameters in Section 4.2.1-4.2.3 use the superscript B because a new parallel route has not yet been considered.

The do-nothing situation is considered as a base case for 1-route analysis. There are only three old lanes (route B) that serve traffic during the peak hour. It is needed only to derive the normal traffic condition of road B before carrying out any further analysis. The steps to calculate the traffic equilibrium of 1-route without toll are as follows:

- The calculation is based on theories in Chapter 3 Section 2.
- First, establish the user cost function (equation 4-2). This part does not yet have equation 4-1 because route A does not exist yet.
- The term for the flat toll τ^B in equation 4-2 is zero as no toll has been imposed yet.
- The inverse demand function for both morning and evening peak hours are presented as equations 4-3 and 4-4, respectively.
- To determine the traffic equilibrium point, the user cost is made equal to the inverse demand function, and N is solved to yield: $N^B_{morning}$ = 14,250 (vehicle/entire peak hour) and $N^B_{evening}$= 19,950 (vehicle/entire peak hour). Figure 4.5 illustrates these intersection points.
- Then, substitute $N^B_{morning}$ and $N^B_{evening}$ back into equation 3-4 to 3-9 to obtain the values of all parameters of interest. The results are shown in Table 5.1, Chapter 5.

- Figure 4.5 presents the calculation results for this section.

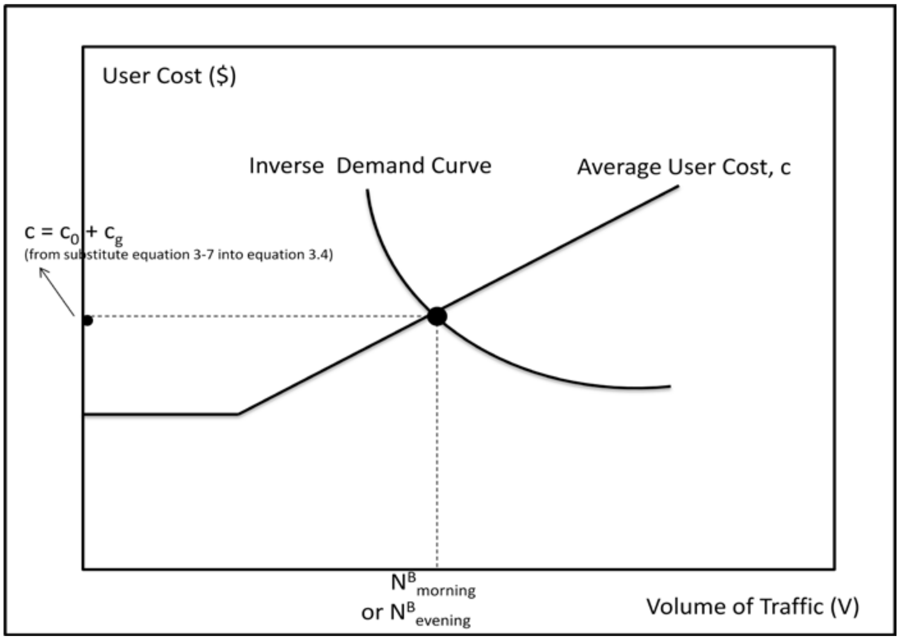

Figure 4.5: The traffic equilibrium of 1-route analysis, no toll

4.2.2 Static pricing and traffic equilibrium for 1 route with flat toll (Static model-1st best pricing)

In this scenario, route B is priced with a flat toll. The analysis follows first-best pricing by (time-averaging) static traffic model.

- The calculation is based on the theories of Section 2.2 and 2.3 of Chapter 2.
- Similar to Section 4.2.1, this analysis uses for route B, the cost function from equation 4-2 and the demand function from equations 4-3 and 4-4. However, in this case, the term τ^B is no longer zero.
- From Chapter 2, Section 2.3 (see equations 2-10 and 2-11), the flat toll that equals marginal cost pricing will maximize the social surplus. That is:

  τ^B = MECC = $MC^B - c^B$ (where MB^B = —— for route B). Note that, τ^B is a function of N.

- Next, substitute τ^B back into equation 4-2 to obtain the full user cost function. Then set the cost function from equation 4.2 = the inverse demand function from equation 4-3 and 4-4 to yield $N^B_{morning}$ and $N^B_{evening}$.
- Finally, the N's are substituted back into equations 2-1 to 2-11 to determine the values of the parameters of interest. These includes the optimal flat toll τ^B = \$ 6.1 for evening peak hour, and = \$4.42 for the morning peak hour.
- Other results are presented in Table 5.1, Chapter 5.
- Figure 4.6 presents the calculation results for this scenario.

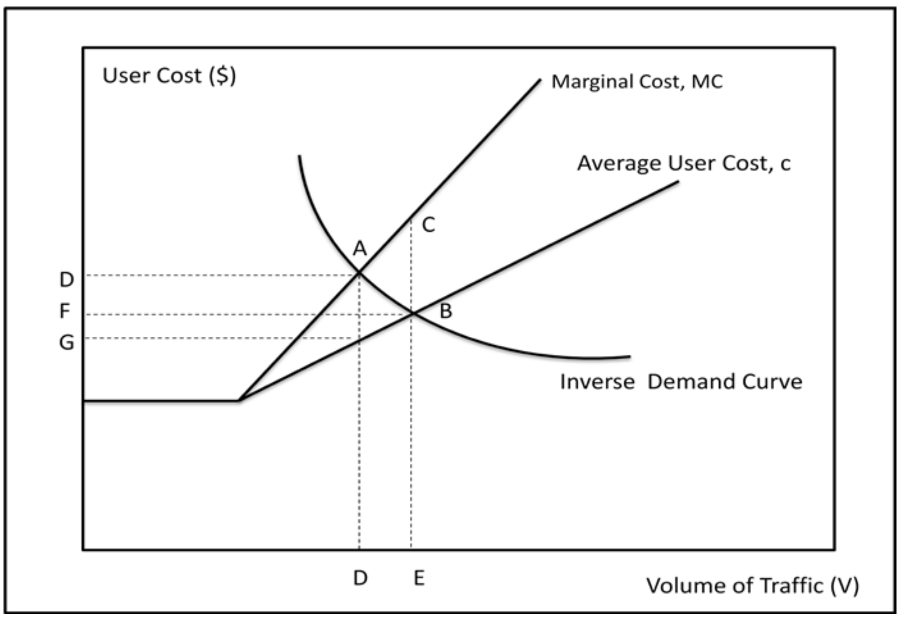

Figure 4.6: The static first-best pricing scheme (1 route)

Figure 4.6 is interpreted and explained in the bullets below. The cost and demand values corresponding to each of the points from A to G are provided in Table 5.1, Chapter 5.

- B is the traffic equilibrium point without any toll imposed. It is the equilibrium that was derived in a previous section (Section 4.2.1).

- A is the new traffic equilibrium point after the static first-best pricing scheme is implemented.
- Length D-E is the decrease in the number of vehicles N after the static first-best pricing scheme is imposed compared to the do-nothing scenario (Section 4.2.1).
- Length D-G represents the optimal flat toll.
- By implementing the static 1^{st} best pricing scheme, users are made to pay the higher user travel cost (length D-F). That is, the total consumer surplus is reduced by an amount equal to the product of (length D-F) and (number of vehicles in the system at point D.)
- On the contrary, the increase in the total social surplus of the entire system = area of triangle ABC.

4.2.3 Dynamic pricing and traffic equilibrium for 1 route with variable toll (Dynamic model-1st best pricing)

In this scenario, the agency implements the dynamic congestion pricing on the 1-route scenario. All theories and equations follow from those in Section 3.2 and 3.3 of Chapter 3.

- The dynamic 1^{st} best pricing toll amount V^B is made to vary but always is equal to the travel time value cost (queuing cost). V^B starts from zero at the beginning of the peak hour and increases linearly to time t^* at the height of the peak period and returns to zero at the end of the peak hour. At each time within the peak period, the toll amount can be calculated using equation 3-10.
- In this scenario, there is no need for the flat toll τ^B to encourage maximum social surplus, so it is set to zero. Readers who seek to satisfy their curiosity may investigate the option of allowing the flat toll to have a positive value in this case and solve for it; it will be found that the value of τ^B is still zero. This would confirm that is already optimal to implement the variable toll V^B without any additional flat toll τ^B.

- The first-best pricing transfers the total deadweight loss of queue to agency revenue without any payoff. As a result, every road user faces the same user cost (which is equal to that for the 1-route equilibrium without toll). The arrival rate at their trip destination (work place), time of the peak hour and the number of users do not change. Only the departure rate from their trip origin (their homes) changes to a value that is equal to the capacity of the entire peak hour.
- Because all road users face the same cost (during the peak hours), the consumer surplus remains the same. The increase in social surplus is equal to the toll revenue which is represented by the area of the triangle ABC in Figure 4.6.
- Moreover, after the dynamic 1^{st} best pricing scheme is in place, the total number of vehicles during the peak hour remains the same. However, the rate of departure from the trip origins (homes) changes from that calculated using equation 3-6 to a new rate that is equal to the system capacity.
- Other results are presented in Table 5.1 of Chapter 5.
- Figure 4.7 below describes the before-implementation and after-implementation situations with regard to the traffic condition and user cost.

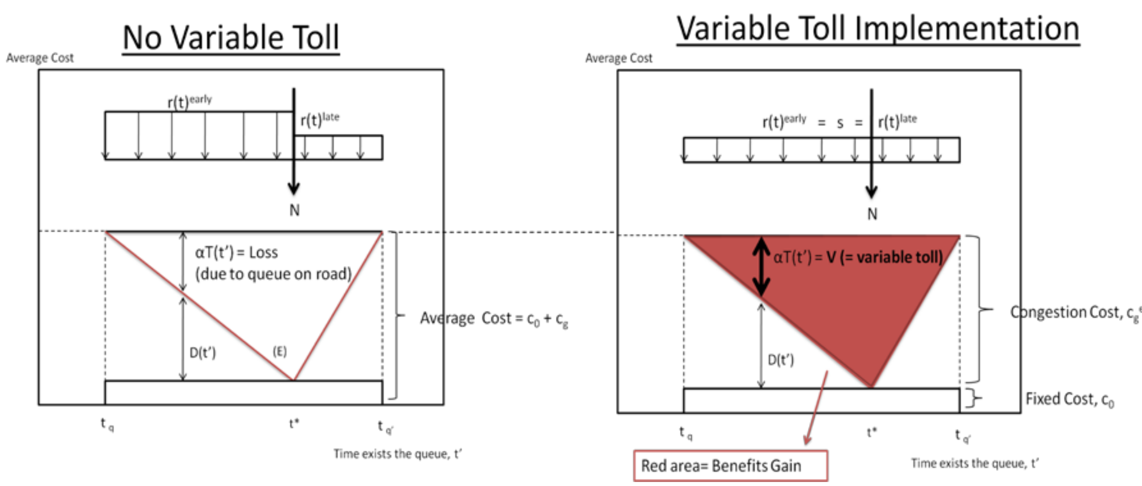

Figure 4.7: Before- and after- implementation of the variable toll, 1-route scenario.

From Figure 4.7, the following important observations can be made:

- At the upper portions of the figure, it is seen that the total number of vehicles, N does not change during the entire peak hour. The only change is the arrival rate to the queue (assumed to be the same as the departure rate from the trip origins) and the departure rate from the queue (assumed to be the same as the arrival rate at the trip destinations). The resulting characteristics for the no-toll situation can be calculated using equation 3-6, and those for the variable toll situation are simply found as they are equal to the road capacity characteristics.
- For both the before- and after- implementation situations of the variable toll, the average user cost is the same because the variable toll (represented by the shaded area) exactly offsets the loss (due to queue on the road).
- The value $\alpha T(t')$, which represents the deadweight loss in the no-toll situation, exactly converts to the variable toll which is the shaded area in the after-implementation situation. For this reason, this amount of revenue is the benefit gain to the agency.

4.2.4 Traffic equilibrium conditions for 2 routes without toll

For this and subsequent scenarios in this chapter, the agency considers building a new lane, route A, parallel to the existing road. First, the traffic equilibrium analysis for the two routes is carried out for the without-toll (or, before-implementation) situation and then for the with-toll (or, after-implementation) situation.

- The analysis is carried out using the theories and equation presented or derived in Section 3.4 of Chapter 3.
- To calculate the traffic equilibrium, the user cost function from equations 4-1 and 4-2, and the demand function from equations 4-3 and 4-4, are used.
- In the without-toll situation where neither route is priced, τ^A and τ^B are zero.
- To determine traffic equilibrium conditions, the cost and inverse demand functions are substituted into equations 3-14, 3-15 and 3-16; and analysis is carried out. The three equations are solved together to yield N^A, N^B and N which are then substituted back to determine all the parameters of interest.

- The results are presented in the “Free Access” column in Tables 5.2 and 5.3 of Chapter 5.

4.2.5 Dynamic pricing and traffic equilibrium for 1 free route and 1 toll route

In this scenario, a dynamic toll is imposed at route A while route B is left free. The analysis and calculation are based on the concepts presented in Section 3.5 of Chapter 3.5.

- Similar to the previous scenario, the inverse demand and user cost functions from equation 4-1 to 4-4, are used in analyzing this scenario.
- It can be noted that the second-best dynamic pricing scheme imposes a toll amount that is the sum of the variable toll and the flat toll. The variable toll is exactly equal to that presented in Section 4.2.3. However, in this scenario, there exists two routes in the system; this makes the variable toll alone no longer optimal. To solve the problem, the flat toll is added to the variable toll for route A.
- To begin with, the optimal flat toll τ^A is calculated using equation 3-18. This flat toll amount helps achieve optimality of the system.
- Next, a calculation process similar to that presented in Section 4.2.4, is followed. The optimal flat toll τ^A and the cost functions are substituted into equations 3-14, 3-15 and 3-16 and these three equations are solved together to yield N^A, N^B, and N. Then these values are substituted back to calculate the values of the parameters of interest.
- The benefit gain can be calculated as the difference between the social surplus of this scenario and that for the 2-route without-toll case (Section 4.2.4). The change of consumer surplus and the number of vehicles can also be compared with the 1-route without-toll case. The social surplus and consumer surplus can be calculated directly using equation 3-17 after obtaining N^A, N^B, and N. For the consumer surplus calculation, refer to the variable descriptions that follow equation 3-17.

- The results are presented in the "Dynamic PUB-Free" columns in Tables 5.2 and 5.3 of Chapter 5.

4.2.6 Static pricing and traffic equilibrium for 1 free route and 1 toll route

In this scenario, the agency implements a flat toll at route A and leaves route B free. The analysis and calculation presented for this scenario are based on the concepts discussed in Section 2.4 of Chapter 4.

- The calculation in this section is generally consistent with that presented in Section 4.2.5, with the exception that in this case, the optimal flat toll is derived using equation 2-18.
- The results for this scenario are presented in the "Static PUB-Free" column of Tables 5.2 and 5.3 in Chapter 5.

It may be noted that for the 2-route analysis, there are still three possible situations that are also of interest:

- Implementing dynamic congestion pricing (both flat and variable toll) on route A and leaving route B free; however, on route A, restrictions are placed on the flat toll amount (it is set to an amount that is greater or equal to zero so that the agency does not end up subsidizing any part of the road user's toll).

- Implementing dynamic congestion pricing (both flat and variable toll) on both routes.

- Implementing static congestion pricing (only flat toll) on both routes.

The analysis and results for these scenarios are presented in the Appendix.

CHAPTER 5 RESULTS AND DISCUSSION

This section presents the results for the 1-route analysis and that for the 2-route analysis, in two sections. Section 5.1 presents the results for the 1-route scenario analysis; this involves only the existing rote (Route B) but no new route, and the section presents the results of calculations from Sections 4.2.1 to 4.2.3 in Chapter 4. Section 5.2 presents the results for the 2-route scenario, where there is a new parallel route (Route A) in addition to the existing route; the results are from the calculations carried out in Sections 4.2.4 to 4.2.6 in Chapter 4.

5.1 Scenarios Involving No New Route

The section presents the calculation results of 1-route scenario which comprises the three alternative situations listed below:

- *1 route, no toll (or, Do-nothing) situation.* The results for the traffic equilibrium analysis associated with this situation are obtained from the calculations in Section 4.2.1 of Chapter 4 (see “Free access” columns in Table 5.1).
- *1 route with flat toll (Static model 1st best pricing) situation*. The results for the static pricing and traffic equilibrium analysis associated with this situation are

obtained from the calculations in Section 4.2.2 of Chapter 4 (see “Static 1st best pricing” columns in Table 5.1).

- *1 route with variable toll (Dynamic model-1st best pricing) situation*. The results for the dynamic pricing and traffic equilibrium analysis associated with this situation are obtained from the calculations in Section 4.2.3 of Chapter 4 (see “Dynamic 1st best pricing” columns in Table 5.1).

Table 5.1: Results for the three Situations of the Single Route Scenario

Parameter	Symbol	Evening Peak hour			Morning Peak hour		
		Free access (do nothing)	Dynamic 1st best pricing (1 route)	Static 1st best pricing (1 route)	Free access (do nothing)	Dynamic 1st best pricing (1 route)	Static 1st best pricing (1 route)
Total of vehicle during peak hour	N^B	19950	19950	14726	14250	14250	10666.7
Flat toll	τ^B	0.00	0.00	6.10	0.00	0.00	4.42
Maximum reschedule delay cost *	$D_{max}{}^B$	8.270	8.270	6.105	5.907	5.907	4.422
Total variable toll collected	V	0	82494	0	0	42089	0
User cost	C	11.1034	11.1034	15.0424	8.74055	8.74055	11.6769
Social surplus	ss	1971680	2054180	1994320	1066740	1108820	1077830
Consumer surplus	CS	1971680	1971680	1904430	1066740	1066740	1030660
Revenue	revenue	0	82494	89895	0	42089	47165
Peak hour peorid	peak_Hr	4.15625	4.15625	3.06791	2.96875	2.96875	2.22222
Different social surplus from free-route	Δss	-	82500	22640	-	42080	11090
Different consumer surplus from free-route	ΔCS	-	0	-67250	-	0	-36080

** This value represents the maximum reschedule delay cost for the persons who first and last exit the queue; for other persons, this represents the sum of the queue cost and reschedule delay cost.*

The discussion of the results for Table 5.1 is carried out mostly for the evening peak hours. A similar discussion can be made for the morning peak hours.

5.1.1 Single Route with no Toll (the Do Nothing or Base Case)

The results for this situation are based on the calculations from Section 4.2.1 of Chapter 4. Figure 5.1 illustrates these results. Figure 4.5 may be compared with Figure 5.1 for better understanding of the latter. The single free-route situation is considered as a default situation or base case for all other situations in this general scenario. There are 19,950 vehicles during the 4.16-hour long evening peak period and 14,250 vehicles during the 3-hour morning peak period. Road users face a user cost $11.1 for the evening peak ($2.83 of VOC + $8.27 of reschedule delay and queue cost) to pass the road section. There is no toll and thus, no revenue.

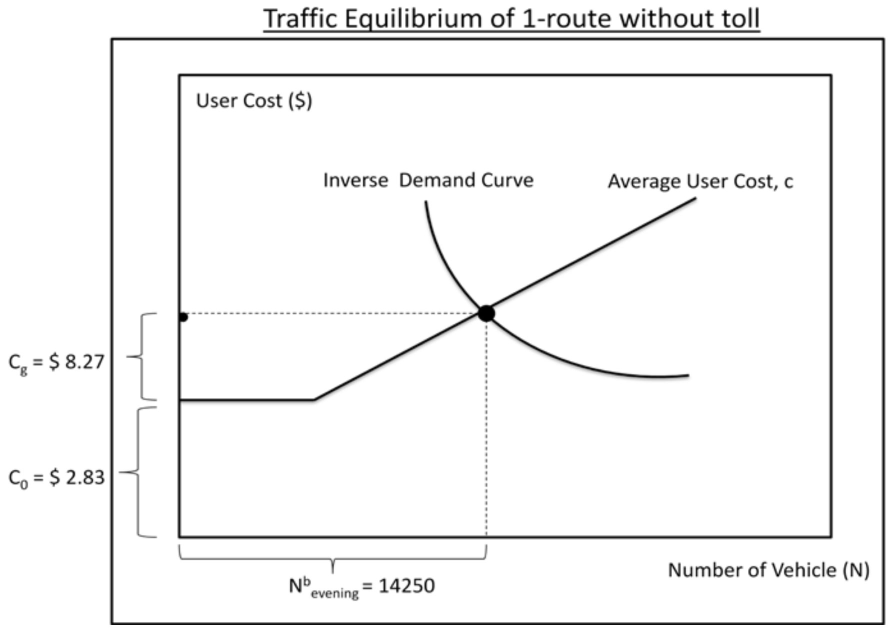

Figure 5.1: Results for the Base Case (Single Free Route)

5.1.2 Discussion for the 1 route with flat toll (the static 1st best pricing situation)

The results for this situation are based on the calculations carried out in Section 4.2.2 of Chapter 4. It is observed that under this scenario, the price paid by road users, in the form of user cost, to use the road is \$15.04 for the evening peak hour which is higher compared with that for the base case (free road) scenario (\$11.1)). Road users are worse off; as a result, fewer travelers use the system. The number of vehicles reduces to 14,726 in the evening (compared with 19,950 in evening peak for the base case scenario (free road)). Due to higher individual user cost, the consumer surplus, naturally reduces from the base case situation of ($\Delta CS = -67250$) during the evening peak hour. In this situation, the flat toll that maximizes social surplus is τ^B = \$6.1 for the evening peak. It may be noted that this optimal from the viewpoint of the static model; however, compared to the dynamic first-best pricing scheme (as will be seen in subsequent sections of this chapter), the result for the static first-best is not better). However, the social surplus for the system in this situation, $ss = CS + revenue$, is higher compared with that of the base case (free road). Δss = 22,640 for the evening peak. Finally, for the entire evening peak hour, the agency will collect a toll revenue of \$89,895. Figure 5.2 illustrates these results.

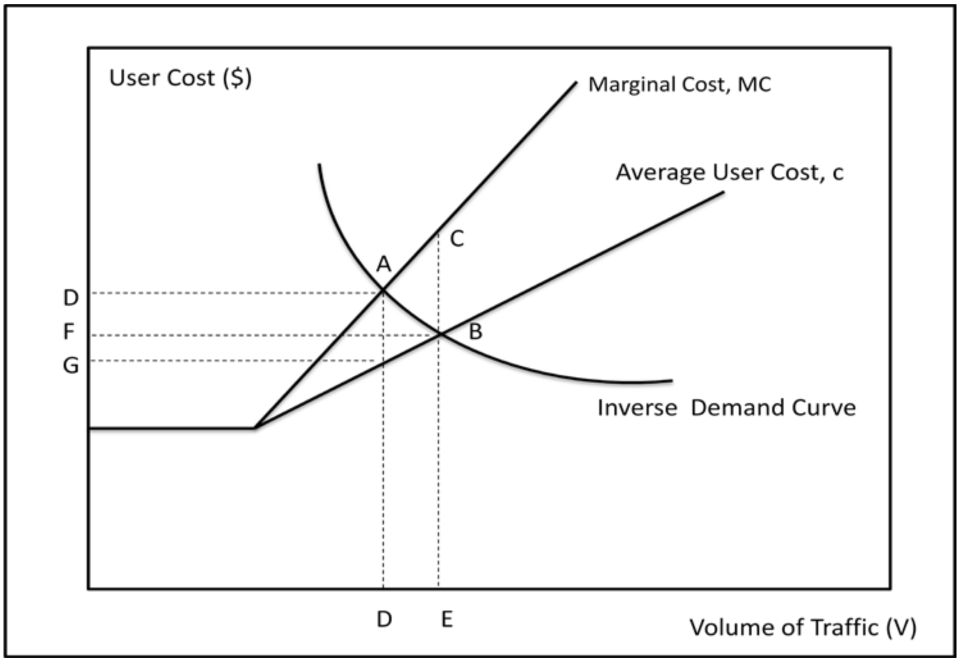

Figure 5.2: Results for the 1-route, static 1st best pricing scheme, evening peak hrs.

Figure 5.2, which is similar to Figure 4.6 in Chapter 4, can be interpreted as follows:

- B is the traffic equilibrium point without any toll implemented. After the static first-best pricing scheme is implemented, the point A is the new traffic equilibrium point.
- The length D-E (19,950 – 14,726 vehicles = 5,224) is the decrease in the number of vehicles N after the static 1st best pricing scheme is in place, compared with the base case (free road, do nothing) situation presented Section 5.1.1.
- The optimal flat toll is equal to length D-G = $ 6.1.
- By implementing the static first-best pricing scheme, road users pay a higher user travel cost = length D-F = ($15.04 – $11.11 = $393). That is, the total consumer surplus is reduced by ΔCS = [(length D-F) * (number of vehicles in the system at point D)] = –67,250.

- On the contrary, there is an increase in the total social surplus of the entire system, Δss = area of triangle ABC = 22,640. The agency collects revenue (for the evening peak period) that is equal to the product of the optimal toll and the number of users, = τ^B * Nr. of users in the evening peak period = $89,895.

5.1.3 Traffic equilibrium for 1 route with variable optimal toll (see columns in Table 5.2 for "Dynamic first-best pricing")

For the dynamic first-best pricing scheme, all results presented herein are based on calculations presented in Section 4.2.3 of Chapter 4. The results presented herein can be interpreted in conjunction with Figure 5.3.

The number of vehicles remains similar to the base case (single route, free access) scenario (= 19,950). Every road user faces the same user cost ($11.1 for the evening peak hours). No road user is worse off. The consumer surplus remains the same as that of the base case situation (that is, $\Delta CS = 0$). The only result that is different from the base case is the departure rate from home. In this scenario, the departure rate will be equal to capacity, *s*, after implementing the variable toll. Here is no queue on road after the toll is implemented. The gain of social surplus compared with that of the base case is the collected revenue, Δss (= 82,494, for evening peak). The variable toll is charge equal to the travel delay cost. It starts from zero at the beginning of peak hour, increases to $8.27 for evening peak and goes down to zero at the end of peak hour. The variable toll produces revenue V (= $ 82,494) for the entire evening peak hours. In this pricing scheme, the variable toll V revenue is equal to total revenue because the flat toll $\tau = 0$. As stated earlier, the flat toll (which encourages the attainment of social optimal) is zero in this case.

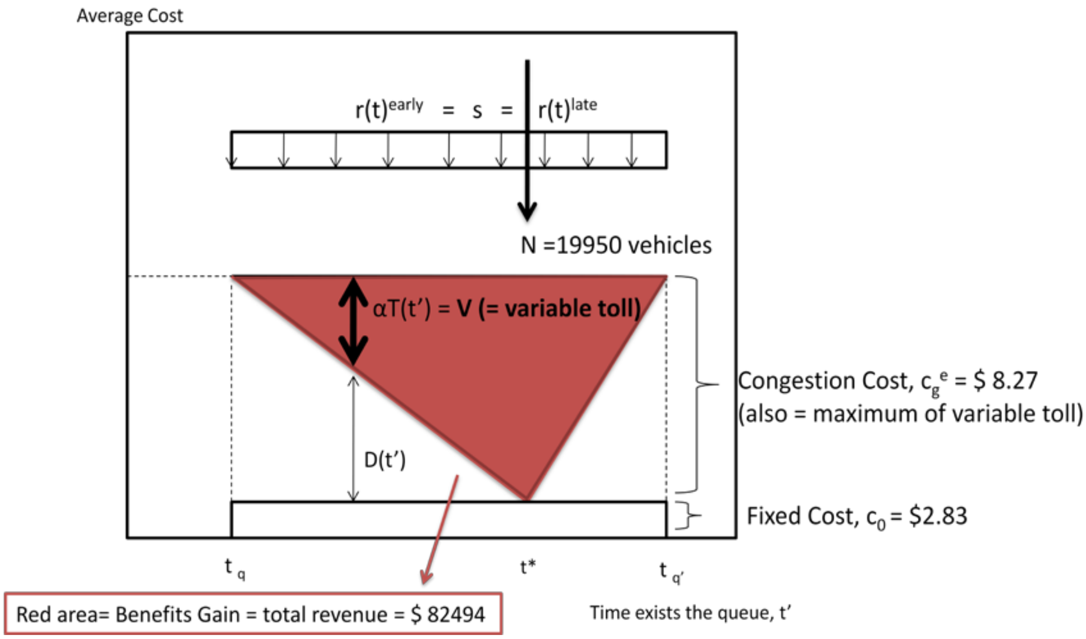

Figure 5.3: Results for the dynamic first-best pricing scheme, evening peak hours.

5.2 Scenarios involving 1old route, B, and 1 new route, A

The section presents the calculation results for the 2-route analyses. This comprises three possible pricing situations:

- *No toll on route A or route B*. The results for traffic equilibrium conditions associated with this situation were obtained from the calculations in Section 4.2.4 of Chapter 4 (see "Free access" columns in Table 5.2).

- *Dynamic congestion pricing (flat & variable toll) on route A, route B free.* The results for implementing dynamic congestion pricing by implementing a flat and variable toll on route A and leaving route B free, were obtained from the calculations in of Section 4.2.5 of Chapter 4 (see "Dynamic PUB-FREE" columns in Table 5.2).

- *Static congestion pricing (flat toll only) on route A, route B free.* The results for implementing static congestion pricing (only flat toll) on route A and leaving route B free were obtained from the calculations in of Section 4.2.6 of Chapter 4. (see “Static PUB-FREE” columns in Table 5.2).

The results of these 3 situations are presented in Table 5.2 and Table 5.3. Table 5.2 presents results of the evening peak hours and Table 5.3 presents those of the morning peak hours.

It may be noted that for the 2-route analysis, there are still three other situations of interest. These situations, results for which are presented in the Appendix, are:

- *Dynamic congestion pricing (flat & variable toll, but with restrictions) on route A, route B free.* See “Dynamic PUB-FREE ($\tau^A \geq 0$)” columns = Implementing dynamic congestion pricing (both flat and variable toll) on route A and leaving route B free. However, the agency imposes some restrictions on route A’s flat toll (it is set to an amount that is greater or equal to zero so that the agency does not end up subsidizing any part of the road user’s toll).

- *Dynamic congestion pricing (flat & variable toll) on both routes A and B.* See “Dynamic PUB-PUB” columns = Implementing dynamic congestion pricing (both flat and variable toll) on both routes.

- *Static congestion pricing (flat toll only) on both routes A and B.* See “Static PUB-PUB” columns = Implementing static congestion pricing (only flat toll) on both routes.

Table 5.2: Results for the 2-route scenario during the evening peak hour

Parameter	Symbol	Evening Peak hour					
		Free access	Dynamic PUB-FREE(τA>=0)	Dynamic PUB-FREE	Static PUB-FREE	Dynamic PUB-PUB	Static PUB-PUB
Total of vehicle during peak hour on both routes	N	22522	22522	23622	21955	22522	16733
Total of vehicle during peak hour on routes A	N^A	5630	5630	7836	4451	5630	4183
Total of vehicle during peak hour on routes B	N^B	16891	16891	15786	17504	16891	12550
Flat toll on route A	τ^A	0.00	0.00	-3.20	1.72	0.00	5.20
Flat toll on route B	τ^B	0.00	0.00	0.00	0.00	0.00	5.20
Maximum reschedule delay cost on route A*	D_{max}^A	7.00	7.00	9.75	5.54	7.00	5.20
Maximum reschedule delay cost on route B*	D_{max}^B	7.00	7.00	6.54	7.26	7.00	5.20
Total variable toll collected on route A	V^A	0.00	19712.60	38181.10	0.00	19712.70	0.00
Total variable toll collected on route B	V^B	0.00	0.00	0.00	0.00	59138.00	0.00
User cost on route A	c^A	9.84	9.84	9.38	10.09	9.84	13.24
User cost on route B	c^B	9.84	9.84	9.38	10.09	9.84	13.24
Social surplus	ss	1998540	2018260	2022210	2000560	2077390	2019780
Consumer surplus	CS	1998540	1998540	2009110	1992900	1998540	1932730
Total revenue	revenue	0.00	19712.60	13097.80	7658.65	78850.60	87051.40
Peak hour peorid on route A	peak_Hr_A	3.52	3.52	4.90	2.78	3.52	2.61
Peak hour peorid on route B	peak_Hr_B	3.52	3.52	3.29	3.65	3.52	2.61
Different social surplus from free-route**	Δss	-	19720	23670	2020	78850	21240
Different consumer surplus from free-route**	ΔCS	-	0	10570	-5640	0	-65810
Efficiency Index***	ω	-	0.250	0.300	0.026	1.000	0.269

* This value represents the maximum reschedule delay cost for the persons who first and last exit the queue; for other persons, this represents the sum of the queue cost and reschedule delay cost.
** Both Δss and ΔCS are measure the difference from the Free access case.
*** Efficiency Index $\omega^G = (ss^G - ss^{FREE-FREE}) / (ss^{PUB-PUB} - ss^{FREE-FREE}) \leq 1$, where ss^G is the social surplus of the interesting pricing scheme (Verhoef, Nijkamp et al. 1996).

Table 5.3: Results for the 2-route scenario during the morning peak hour

Parameter	Symbol	Morning Peak hour					
		Free access	Dynamic PUB-FREE(τA>=0)	Dynamic PUB-FREE	Static PUB-FREE	Dynamic PUB-PUB	Static PUB-PUB
Total of vehicle during peak hour on both routes	N	15971	15971	16738	15616	15971	12057
Total of vehicle during peak hour on routes A	N^A	3993	3993	5623	3209	3993	3014
Total of vehicle during peak hour on routes B	N^B	11978	11978	11116	12406	11978	9043
Flat toll on route A	τ^A	0.00	0.00	-2.38	1.15	0.00	3.75
Flat toll on route B	τ^B	0.00	0.00	0.00	0.00	0.00	3.75
Maximum reschedule delay cost on route A*	D_{max}^A	4.97	4.97	6.99	3.99	4.97	3.75
Maximum reschedule delay cost on route B*	D_{max}^B	4.97	4.97	4.61	5.14	4.97	3.75
Total variable toll collected on route A	V^A	0.00	9912.78	19657.50	0.00	9912.78	0.00
Total variable toll collected on route B	V^B	0.00	0.00	0.00	0.00	29738.30	0.00
User cost on route A	c^A	7.80	7.80	7.44	7.98	7.80	10.33
User cost on route B	c^B	7.80	7.80	7.44	7.98	7.80	10.33
Social surplus	ss	1080940	1090850	1093030	1081830	1120590	1091120
Consumer surplus	CS	1080940	1080940	1086780	1078130	1080940	1045920
Total revenue	revenue	0.00	9912.78	6250.70	3696.89	39651.10	45195.90
Peak hour peorid on route A	peak_Hr_A	2.50	2.50	3.51	2.01	2.50	1.88
Peak hour peorid on route B	peak_Hr_B	2.50	2.50	2.32	2.58	2.50	1.88
Different social surplus from free-route**	Δss	-	9910	12090	890	39650	10180
Different consumer surplus from free-route**	ΔCS	-	0	5840	-2810	0	-35020
Efficiency Index***	ω	-	0.250	0.305	0.022	1.000	0.257

* This value represents the maximum reschedule delay cost for the persons who first and last exit the queue; for other persons, this represents the sum of the queue cost and reschedule delay cost.
** Both Δss and ΔCS are measure the difference from the Free access case.
*** Efficiency Index $\omega^G = (ss^G - ss^{FREE-FREE}) / (ss^{PUB-PUB} - ss^{FREE-FREE}) \leq 1$, where ss^G is the social surplus of the interesting pricing scheme (Verhoef, Nijkamp et al. 1996).

The discussion of the results for Table 5.2 is carried out mostly for the evening peak hours. A similar discussion can be made for the morning peak hours. A discussion of the three situations involving the new route is presented in the ensuing sections.

5.2.1 Free access on 2 routes (both A and B are free to access.)

In this situation, the agency builds a new free lane, route A, as an alternative to route B. In this situation, the traffic equilibrium yields an increase in the number of vehicles during evening peak hour to 22,522 – often such increases can be attributed to induced traffic. This results in a 2.5 hour evening peak period. The traffic split during the evening peak hour is: route A, 5,630 vehicles; route B, 16,891 vehicles. As both routes are free, both the flat toll τ and the variable toll V are still zero for this pricing scenario. To use the road sections, each road user faces a user cost equal to \$9.84 (assume equal levels of road surface roughness and other VOC factors across the two alternative routes). Figure 5.4 illustrates the traffic equilibrium between the two routes.

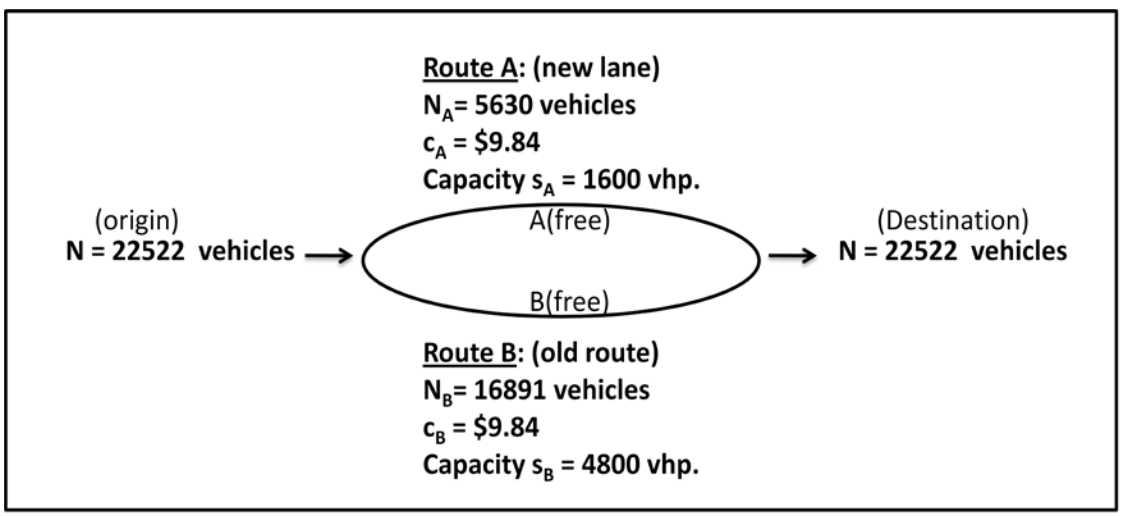

Figure 5.4: Traffic equilibrium of 2-route with free access, evening peak hours.

In order to acquire some insight of the traffic equilibrium associated with the 2-free-routes base case situation, it is compared with the traffic equilibrium associated with the 1-free-route base case situation (Section 5.1.1). The results for the 2-free-routes scenario, compared with the 1-free-route scenario, are discussed in the bullets that follow below.

- By constructing the new route A, the agency reduces the average user cost to \$9.84 (compared with \$11.1 in the 1-free-route scenario (Section 5.1.1)).
- Due to the reduced user cost, the number of users increases to 22,522 vehicles per peak period (compared with 19,950 vehicles per peak period in the 1-free-route scenario (Section 5.1.1)).
- The length of the peak hour is 2.5 hours (a reduction by 1.7 hours, compared to 4.2 hours in the 1-free-route scenario (Section 5.1.1)).
- Finally, the consumer surplus (and social surplus) increases compared to the 1-free-route scenario the agency builds a new road and leaves both old and new road free. $\Delta CS = \Delta ss$ = 1,998,540 – 1,971,680 (\$-vehicle) = \$26,860.

For all road pricing scenarios involving two alternative routes (results of which are discussed in subsequent sections), the 2-free-routes situation serves as the base case, for purposes of comparison across the situations associated with the general 2-routes scenario, in terms of the social surplus, consumer surplus and benefit gain.

5.2.2 Dynamic PUB-FREE (price only on route A with flat and variable toll)

For all practical purposes, this pricing scheme is relatively more practical to implement compared to other schemes discussed subsequently. The agency leaves the old route B as a free route and builds a new route A at which a toll is imposed. The variable toll on route A, which is set at a level that is equal to the travel delay cost, starts from zero at beginning of peak hour, increases to \$9.75 and decreases to zero at the end of the peak hour. In addition, the agency charges a flat toll τ^A in addition to the variable toll in a bid to attain maximum social surplus. The result is that τ^A = –\$3.2. This means the agency will subsidize each vehicle’s toll to the tune of \$3.2. However, when combined with the variable toll revenue, the agency still makes revenue equal to 13,097 for the entire evening peak hour.

In this pricing scheme, no one worse off and both consumer and social surplus increase, ΔCS = 1,057 and Δss = 23,670 (compared with the 2-free-routes situation in Section 5.2.1). The average user cost also decreases to \$9.38, compared with \$9.81 of 2-free-routes situation in Section 5.2.1. Due to the decrease of average user cost, an increased number of road users (vehicles) use the system (N = 23,622), and the split is as follows: route A, N^A= 7,836 and route B, N^B = 15,786. Finally, the efficiency index ω= 0.3 which suggest that the dynamic first-best pricing scheme has 30% efficiency.

This index ω can be used to measure the level of social surplus of this scenario compared with that of the dynamic first-best pricing scheme. The efficiency index could be interpreted as the relative "goodness" of a pricing scheme compared to the 2-free-route scenario (the PUB-PUB pricing scheme). Specifically, the efficiency index of pricing scheme G, $\omega^G = (ss^G - ss^{\text{FREE-FREE}}) / (ss^{\text{PUB-PUB}} - ss^{\text{FREE-FREE}})$, where G = [dynamic PUB-FREE, static PUB-PUB, etc.] (Verhoef, Nijkamp et al. 1996; PalmaI and Lindsey 2000).

Figure 5.5 describes the traffic pattern of "dynamic pub-free" scenario (that is, the imposition of a flat and variable toll on route A).

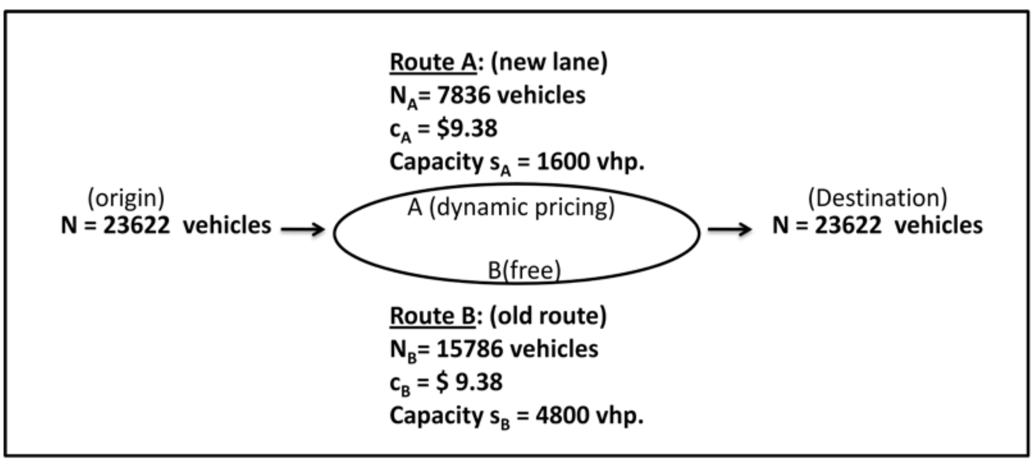

Figure 5.5: Traffic equilibrium for the dynamic 2nd pricing scheme 2-route parallel (flat and variable toll at route A), evening peak hours.

5.2.3 Static PUB-FREE (price only on route A with flat toll)

In this scenario, the agency imposes a flat toll τ^A of \$1.72 (obtained through solution based on social welfare maximization) on new route A. With this, road users, on average, become worse off compared to the base case. Road users pay the higher price, *c*, to use the road section (*c* = \$10.09), and the total consumer surplus (*CS*) reduces compared to the base case (the 2-free-route situation) by an amount ΔCS = –5,640. However, the social surplus of the system still increases: Δss = 2,020. The value of *ss* due to the revenue is \$7,659 (*ss* = *CS* + revenue) which offsets the negative *CS*. Due to the reduction in *CS* and increase in user cost, the number of vehicles that use the system reduces to N = 21,955 and are split as follows: Route A: N^A = 4,451 and Route B: N^B = 17,504, compared to the 2-free-route situation (Section 5.2.1). The efficiency index ω is only 0.03, that is, 3%. Figure 5.6 below describes the traffic distribution associated with this situation.

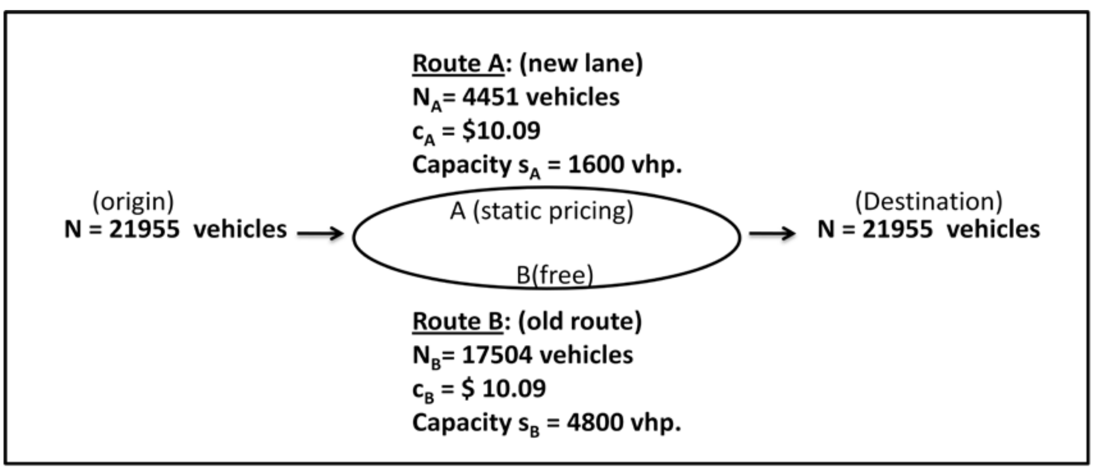

Figure 5.6: Traffic equilibrium for the static 2nd pricing scheme 2-route parallel (flat toll at route A), evening peak hours.

CHAPTER 6 FINANCIAL FEASIBILITY ANALYSIS

The previous chapter derived the optimal toll and traffic equilibrium associated with a number of pricing schemes. In this chapter, the focus is on two pricing schemes that both involve new road construction; static and dynamic 2nd best pricing scheme (i.e., the Static and Dynamic PUB-FREE situations discussed in the previous chapters). In these two pricing schemes, the agency builds the new road (route A) and investigates the impacts of tolling new road for either case of static or dynamic pricing. Figure 6.1 illustrates these situations.

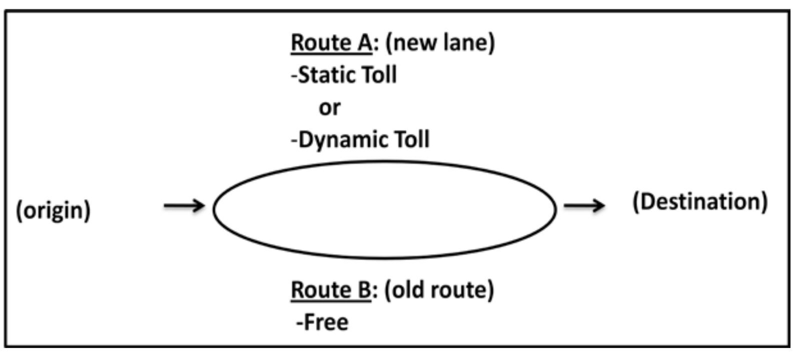

Figure 6.1: Static or Dynamic 2nd best pricing scheme that toll Route A only

This report focuses on these two pricing schemes because they can be considered the most practical in the real world. For instance, for an existing congested highway, it obviously makes little sense to impose a toll without any alternatives to road users, as that would likely lead to a public relations disaster. Instead, the agency may consider expanding the road or building an alternative parallel road. While this seems to be a good solution, there are two serious issues about this solution: first, the new road and the old one will soon face the same congestion problem due to induced traffic demand. Because the new road reduces the cost of the trip, it will attract more demand from existing routes or other minor routes. Second, transportation systems in the current era face funding limitations due to tighter budgets. Thus, instead of just building a new free road, the agency could consider tolling it and channel any collected revenue towards reconstruction, maintenance, and operations. In that case, the existing road will still be left as a free travelling alternative. For the new road, imposition of a toll could help prevent or reduce traffic congestion (or the rate of increase thereof) as it helps control the level of road user cost. However, the long-term impact of congestion pricing is still not clear: in the long term, traffic congestion might grow back up. If this is really the case, then the pricing scheme can at least help defer the time at which this would happen, and in the meantime generate revenue for implementing future road widening, Intelligent Transportation System (ITS) technologies, or other capacity-enhancing initiatives.

The purpose of this chapter is to ascertain whether the revenue from collected toll would be adequate to cover the capital and operating costs of the new tolled road. Where necessary, the traffic condition improvement is also restated to highlight the benefits of the two pricing schemes. The outline of the chapter is as follows: first, the assumptions of capital and operating conditions are established, and then the capital and operating costs are estimated. Second, the key elements of the scenario of building a new road with static pricing are presented. The topics of discussion include financial feasibility analysis, congestion mitigation, and the advantages and disadvantages of the static pricing scheme. Third, the dynamic pricing scheme for the new road is presented and discussed.

6.1 The capital and operating cost of a new toll road

Capital Cost Assumptions:

To calculate financial feasibility, the following assumptions are made.

- The new road is one-lane, located on the median of the old road of the Interstate 69 highway. Thus, there is no cost involved in right-of-way acquisition. The new toll road is 6-mile in length with two access points at the two ends located in the median of existing facility.

- Assume implementation year is 2020, interest rate is 2.5%. (Dollar amounts presented in Chapter 5 are in USD 2008, and are adjusted to year USD 2020).

For the capital cost,

- The unit cost of pavement = $957,000 per lane-mile in 2005 USD. This is the unit cost of principal arterial class (Sinha and Labi 2007).
- Thus, the total pavement cost for 6 mile and 1 lane, in USD year 2020 = $8,316,128.
- A transponder issued to road users or a license photo plate technology is used to collect the toll. The latter is the same as that at I-25 in Colorado. The list of tolling infrastructure is presented in Table 6.1.
- Combining all capital cost and converting to year 2020, we received the capital cost = $9,436,293 (USD year 2020).

Table 6.1: Tolling infrastructure costs. Source: (Davis III 2008)

Description	Quantity Per Toll Lane	Unit Cost (2005)	Total Materials (2005)	Total Labor (2005)	Total Cost (2005)	Total Cost (Implementing year)
Antenna	2	$2,500	$10,000	$1,200	$11,200	$16,221
ETC reader	1	$1,300	$2,600	$600	$3,200	$4,635
ETC reader/controller	1	$7,300	$14,600	$600	$15,200	$22,014
CCTV violation cameras	2	$5,200	$20,800	$1,600	$22,400	$32,442
Power	1				$2,500	$3,621
Lane controller	1	$11,400	$22,800	$1,600	$24,400	$35,338
Support structure	1	$45,000	$90,000	$2,400	$92,400	$133,823
Support foundation	1	$7,000	$14,000	$2,400	$16,400	$23,752
Communications interface	-				$5,000	$7,241
Local field processing equipment and software	-				$100,000	$144,830
Integration and toll tag tracking	-				$300,000	$434,489
detection loops	3	$75	$450	$1,800	$2,250	$3,259
30% Contingencies						$258,499
TOTAL						$1,120,164

For operation cost,

- This report uses the operating and maintenance cost of project I-25, Colorado, which share the most similar operating and facility characteristics. The operation cost is estimated as follows: $2,593,408.98/year at 2020 (or $2,498,533/year in 2008). (Enterprise July 2007- June 2009)

6.2 Analyzing the feasibility of static pricing at the new road (while keeping the old road free)

This section discusses the financial feasibility of imposing static pricing on the new road while keeping the old (existing) road free. First, a number of assumptions are made for estimating the annual revenue from the new road. Then the difference between the annual revenue and the annual operating cost is found (this is the annual net revenue). The net annual revenue and the interest rate are then used to calculate the payback period.

Revenue Calculation

The toll revenue for the 2nd-best pricing 2-route parallel is calculated for both the static and dynamic scenarios. All assumptions made in Chapter 5 are valid in these computations. Also, it is assumed that the toll revenue growth rate is 2.5% annually; the facility operates 200 days a year, and the toll is charged at both morning and evening peak hours. Table 6.2 below shows the calculation of net annual revenue of the Static PUB-Free pricing scheme in year 2020. The net annual revenue = Annual revenue – Annual operating cost.

Table 6.2: Net annual revenue for the Static PUB-FREE pricing scheme (Year 2020$)

2-Route Pricing Scheme	Evening Peak Revenue	Morning Peak Revenue	Total daily revenue	Annual Revenue ($ year 2020)	Annual Net Revenue (Revenue - Annual operating cost)
Static PUB-FREE	$7,659	$3,697	$11,356	$3,054,388	$460,979

From Table 6.2, the daily toll revenue is equal $(7,659 + 3,697) = $ 11,356 per day. Assuming 200 operating days per year, the annual revenue is = 200($11,356) = $460,979 per year (for year 2010).

Finally, the net annual revenue = Annual revenue – Annual operating cost ($2,593,410 USD/year in 2020).

Given the assumption of 2.5 % interest rate and 2.5 % revenue growth rate, the net annual revenue for the year following 2010 can be calculated. The first 3 columns in Table 6.3 presents the results of this calculation. The last column of the table also provides the calculation of the payback time for the capital cost. The capital cost leftover at any year is equal to (the operating cost left from previous year) – (the net annual revenue).

Table 6.3: The payback time calculation of Static 2-route parallel pricing scheme with only tolling 1 route (Static PUB-FREE scheme)

Year	The annual operation cost	The annual revenue	The net annual revenue	The capital cost leftover (already consider over time)
2,020	$2,593,409	$3,054,388	$460,979	$6,364,406
2,021	$2,658,244	$3,130,747	$472,503	$6,051,013
2,022	$2,724,700	$3,209,016	$484,316	$5,717,973
2,023	$2,792,818	$3,289,242	$496,424	$5,364,498
2,024	$2,862,638	$3,371,473	$508,834	$4,989,777
2,025	$2,934,204	$3,455,759	$521,555	$4,592,966
2,026	$3,007,559	$3,542,153	$534,594	$4,173,196
2,027	$3,082,748	$3,630,707	$547,959	$3,729,567
2,028	$3,159,817	$3,721,475	$561,658	$3,261,148
2,029	$3,238,812	$3,814,512	$575,699	$2,766,978
2,030	$3,319,783	$3,909,875	$590,092	$2,246,060
2,031	$3,402,777	$4,007,621	$604,844	$1,697,368
2,032	$3,487,847	$4,107,812	$619,965	$1,119,837
2,033	$3,575,043	$4,210,507	$635,464	$512,368
2,034	$3,664,419	$4,315,770	$651,351	$0

The results suggest that the Static PUB-FREE pricing scheme will take approximately 15 years to pay back the capital cost (that is, at the end of year 2034). If a different interest rate is used, the payback time will also be different. Figure 6.2 illustrates the expected change in payback period in response to a change in the interest rate.

In addition to achieving self-finance of the new road, the agency could also reduce congestion during the peak hours of the system (that is, routes A and B). From Chapter 5, it can be seen that if the agency builds the new road without imposing any toll, there will be 22,522 vehicles during the evening peak hour and 15,971 vehicles during the morning peak hour. By imposing the static toll on the new road, the agency could encourage road users to cancel non-essential trips during peak hours. As the result, traffic volume can reduce to 21,955 vehicles during the evening peak hour and 15,616 vehicles during the morning peak hour.

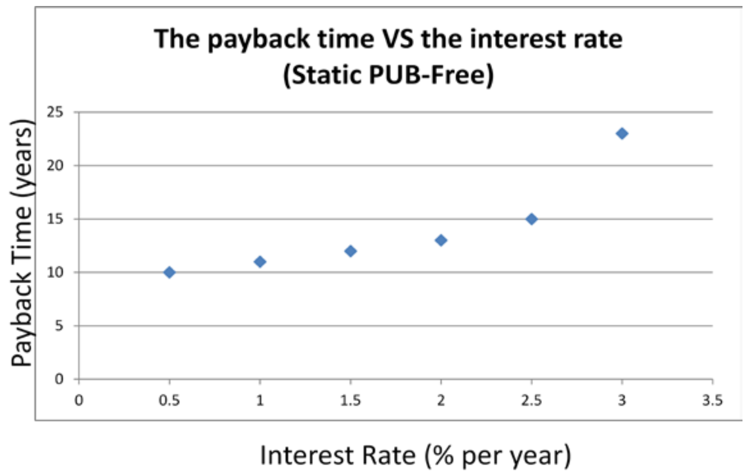

Figure 6.2: Sensitivity of payback period to interest rate, Static PUB-Free pricing scheme

6.3 The feasibility analysis of the dynamic pricing scheme on the new road (while keeping the old road free to access)

This section discusses the financial feasibility of implementing a dynamic pricing scheme for the new road. In a manner similar to that carried out for the static pricing scenario, the analysis begins with the assumptions for estimating the annual revenue after the scheme implementation.

Revenue Calculation

All the assumptions made in Section 6.1 are valid in this analysis. The only difference is that the new road, in this case, is priced dynamically. Table 6.4 presents the calculation of net annual revenue of the Dynamic PUB-Free pricing scheme in year 2020. The net annual revenue for each year, which is calculated as the difference between annual revenue and annual operating cost, is used to calculate the payback period.

Table 6.4: Net annual revenue for the Dynamic PUB-FREE pricing scheme (Year 2020$)

2-Route Pricing Scheme	Evening Peak Revenue	Morning Peak Revenue	Total daily revenue	Annual Revenue ($ year 2020)	Annual Net Revenue (Revenue - Annual operating cost)
Dynamic PUB-FREE	$13,098	$6,251	$19,349	$5,204,316	$2,610,907

From Table 6.4, the daily toll revenue is $(13,098 + 6,251) = $ 19,349. Assuming 200 operating days per year, the annual revenue is 200($19349) = $5,204,316 per year (for year 2010). Finally, the net annual revenue = Annual revenue – Annual operating cost ($2,593,410 USD/year in 2020, as stated in the previous chapter).

With the assumption of 2.5 % interest rate and 2.5 % revenue growth rate, the net annual revenue for the year following 2010, can be calculated. The first three columns in Table 6.5 show this calculation. The last column of Table 6.5 presents the results of the calculation of the payback time of the capital cost. At any year, the capital cost that is left over is equal to the operating cost left from previous year less the net annual revenue.

Table 6.5: Payback period for the Dynamic 2-route parallel pricing scheme with only tolling 1 route (Dynamic PUB-FREE scheme)

Year	The annual operation cost	The annual revenue	The net annual revenue	The capital cost leftover (already consider over time)
2,020	$2,593,409	$5,204,316	$2,610,907	$6,825,385
2,021	$2,658,244	$5,334,424	$2,676,180	$4,319,840
2,022	$2,724,700	$5,467,785	$2,743,084	$1,684,751
2,023	$2,792,818	$5,604,479	$2,811,662	$0

The results suggest that the Dynamic PUB-FREE pricing scheme will take approximately four years to pay back the capital cost (that is, at the end of year 2023). If the interest rate changes, the payback period will change. Figure 6.3 presents the pattern of the change of payback time in response to a change in interest rate.

In addition to the self-finance of this new road, the agency can reduce congestion during the peak hours of the system. However, the traffic equilibrium for the dynamic congestion pricing situation will be different from that for the static situation. As discussed in Chapter 5, the dynamic 2nd-best pricing scheme will induce additional traffic to the system because of the lower total user cost associated with that scheme. However, this does not necessarily mean that there will be more congestion because the peak hour is extended. The extension of the peak hour is a feature, even an advantage, of the dynamic pricing scheme.

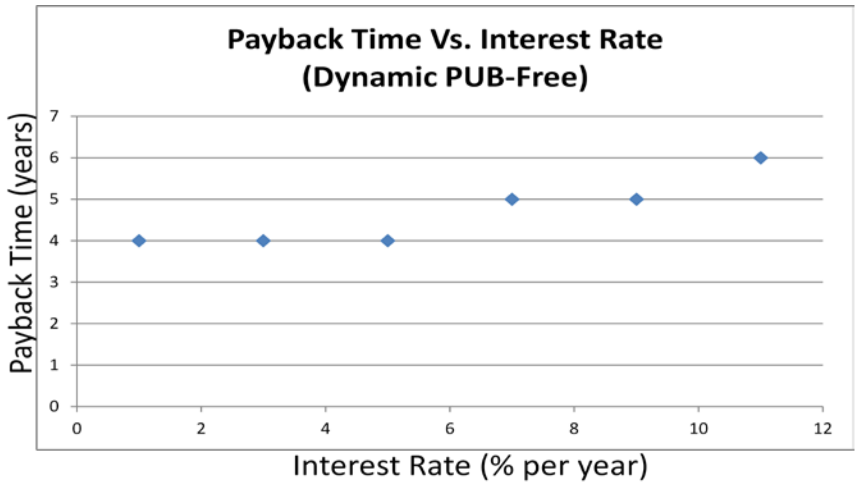

Figure 6.3: Sensitivity of the payback period to interest rate, the Dynamic PUB-Free pricing scheme

CHAPTER 7 SUMMARY AND CONCLUSIONS

The report provided an overview of the evolution and concept of congestion pricing. This was followed by a presentation of the concepts associated with user cost estimation. The fixed user cost does not vary with the level of traffic congestion and could include vehicle operating cost and fuel cost. The variable user cost or congestion cost depends on the level of traffic and is what renders the dynamic traffic model as being distinct from the static model. For static congestion pricing, the congestion cost is developed from the time-independent traffic model, while for dynamic congestion pricing this is done using the time-dependent traffic model. For the time-dependent model, it is possible to incorporate schedule delay cost into the model.

After developing the user cost function, the report described the static congestion pricing scheme. The concept of a link performance function was discussed. The report then developed the traffic model, followed by the static user cost function. The user cost was used with the inverse demand to serve as the basis for the static 1st-best pricing or marginal-cost pricing, and the classic "2-route parallel" scenario was examined.

The report also addressed the concept underlying the implementation of dynamic congestion pricing, including a review of bottleneck traffic modeling. The dynamic user cost function was developed and the dynamic 1st-best pricing scheme was derived. The report implements the concepts using a case study involving Interstate 69 highway at Indianapolis. For each possible pricing situation under each scenario, the report discusses the corresponding traffic equilibrium condition, toll rate, consumer surplus and other outcome parameters. For the implementation feasibility analysis, the most practical pricing schemes, the static and dynamic 2nd-best pricing schemes, were used. The goal of the feasibility analysis was to ascertain whether the toll revenue would be adequate is enough to cover the cost of implementation. The report calculated the costs and revenue associated with each of these two schemes and estimated the corresponding payback period for the investment.

Overall, it is shown that congestion pricing not only generates revenue but also is a way of harnessing the power of the market to reduce the waste associated with traffic congestion thus inducing more efficient use of transport infrastructure. As demonstrated in the case study, introducing congestion pricing on highway facilities can help discourage overuse during rush hours by motivating travelers to use other modes such as carpools or transit, or by traveling at other times of the day. By removing a fraction (even as small as 5%) of the vehicles from a congested roadway, congestion pricing can enable the system to flow much more efficiently, allowing more cars to move through the same physical space. Thus, the case study for a selected stretch of the Interstate 69 highway in Indianapolis showed that it is feasible to implement congestion pricing at the selected corridor and that such implementation can yield significant benefits in terms of congestion mitigation and revenue generation.

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APPENDICES

APPENDIX A

This section divides the interesting literature into categories. The detail is in the table below.

Categories	Reference
Economic theories and congestion pricing: The following textbooks and papers provide reviews on microeconomics and nonlinear optimization theories that are necessary for congestion pricing analysis.	(Chris Jensen-Butler, Birgitte Sloth et al. 2008) (Mas-Colell, Whinston et al. 1995) (McCarthy 2001) (Nicholson 2002) (Santos 2004) (Small and Verhoef 2007)
Basic traffic modeling	(Hall 2003) (Sheffi 1985)
Broad perspective of congestion pricing	(Federal Highway Administration 2006) (Lindsey 2006) (Ubbels) (Verhoef 2008)
Basic congestion pricing analysis: The simple 1^{st} best static/dynamic analysis of congestion pricing.	(Button 2004) (McCarthy 2001) (Lindsey and Verhoef 2000a) (Small and Verhoef 2007)
Risk analysis of congestion pricing: Financial risk due to traffic prediction and other factors	(Chu and Tsai 2004) (Lemp and Kockelman 2009) (Wibowo, S.M.ASCE et al. 2005)
Dynamic congestion pricing, 1-route case: 1-route case with both 1^{st} and 2^{nd} best. The bottleneck model is used.	(Arnott, Palma et al. 1993) (Arnott, Palma et al. 1990) (Braid 1989) (Roichard Arnott, Andre De Palma et al. 1993)
Dynamic congestion pricing, 2-route parallel: 2-route parallel case with both 1^{st} and 2^{nd} best. The bottleneck model is used.	(Arnott, Palma et al. 1990) (Braid 1996)
Dynamic congestion pricing, 2 modes of travel compete: For example, road competes with rail.	(Arnott and Yan 2000) (Verhoef, Nijkamp et al. 1996)
Investment theories of congestion pricing: This includes cost recovery theorem, optimal level of road capacity, etc.	(Borger, Dunkerley et al. 2009) (D'Ouville and McDonald 1990) (Lindsey 2009) (Mohring and Harwitz 1962) (Verhoef 2004) (Verhoef and Mohring 2009) (Vickrey 1969) (Wheaton 1978) (Wilson 1983) (Yang and Meng 2000) (Yang and Meng 2002)

Taxation and funding theory: The way to fund the road network, not at the project level.	(TRB 2006) (Fowkes, Mackie et al. 1985) (Walters 1961)
The congestion pricing with user heterogeneity: One form of 2nd best pricing with different marginal cost among each group of users. The difference of groups implies the difference in travel time, speed, information, etc.	(Arnott and Kraus 1998) (Chu and Tsai 2004) (Palma and Lindsey 2004) (Powell 1985) (Small and Yan 2001) (Verhoef, Nijkamp et al. 1995) (Verhoef, Rouwendal et al. 1999) (Verhoef and Small 1999)
The general impact of congestion pricing implementation: For example, impact of congestion on bus system, etc.	(Bilbao-Ubillos 2008) (Santos and Rojey 2004) (Small 2003) (Zhang and Levinson 2009)
Traffic modeling in congestion pricing: In this report, we use the linear piecewise and bottleneck traffic model, but there is still other traffic models used in the field. Each model has different strengths and weak points.	(Bradford 1996) (Lindsey and Verhoef 2000b) (Verhoef 1999) (Verhoef 2001) (Verhoef 2003) (Verhoef 2005) (Verhoef and Rouwendal 2004)
The ownership of toll system: For example, two private roads compete, or private competes with an agency/owner of toll road, etc. The game theory is the principal tool.	(Berenbrink and Schulte 2007) (PalmaI and Lindsey 2000) (Ubbels and Verhoef 2008) (Ubbels and Verhoef 2008)
Travel time issue in congestion pricing:	(Rouwendal, Blaeij et al. 2009) (Small 1982) (Tseng and Verhoef 2008) (Yamamoto, Fujii et al. 2000)
Congestion charge due to multi objective and constraints	(Sumalee, Shepherd et al. 2009)
Road network pricing:	(Emrnerink, Verhoef et al. 1997) (Verhoef, Nijkamp et al. 1995) (Verhoef 2000) (Verhoef 2002a) (Verhoef 2002b) (Verhoef 2002c)
Stochastic information in congestion pricing: This means uncertainty in information of demand, capacity, etc.	(Arnott, Palma et al. 1996) (Emmerink, Verhoef et al. 1998) (Verhoef, Emmerink et al. 1995) (Verhoef, Koh et al. 2009) (Yang 1999)

The implementation of congestion pricing: There are many issues in putting congestion pricing into implementation.	(Brathen and Odeck 2009) (Kriger, Shiu et al. 2006) (Davis III 2008) (Dusica Joksimovic, Dirk H. van Amelsfort et al.) (Ecola and Light 2009) (Fields, Hartgen et al. 2009) (Guo and Yang 2009) (Lindsey 2009a) (Lindsey 2009b) (Sandholm 2002) (Tsekeris and Voß 2009) (Verhoef 1995)
Air pollution pricing	(Nash, Sansom et al. 2001) (Verhoef, Nijkamp et al. 1995)
Other externality pricing: In this report, the externality cost is only delay time, but it can include air pollution, social impact, etc.	(Arnott 2007) (Blaeij, Florax et al. 2003) (Small and Dender 2005) (Verhoef 1994) (Verhoef 2005) (Verhoef and Nijkamp 1999) (Verhoef and Rouwendal 2004)
The optimal location of congestion pricing project	(Chu and Tsai 2008) (Yang and Zhang 2003)
Congestion pricing in the airline industry	(Pels and Verhoef 2004) (Verhoef 2009)
The implementation of ITS in congestion pricing	(Zhang and Verhoef 2006)
Auction of congestion pricing project	(Ubbels and Verhoef 2008) (Verhoef 2007)
Use of parking policies in congestion pricing	(Verhoef 1995)
Alternative theory of congestion pricing: In some circumstance, the classic theory might not promote the optimal system. An alternative theory is needed to use.	(Brueckner and Verhoef 2009)

APPENDIX B

This section presents the experience of congestion pricing worldwide. The projects include those at London, Stockholm, Ontario’s Highway 407 express toll route, Orange County, California’s SR-91 express lanes, San Diego, California’s I-15 express lanes. The details of each project are presented below.

London's Congestion Charging zone

Evolution

The idea of area congestion charge for London began in the early 1960s. UK’s ministry of transportation established a panel study headed by Professor R.J. Smeed to examine the feasibility of road pricing. Smeed’s report, which was published in 1964, indicated the benefits of congestion charges and indicated that the benefits of congestion charges were positive even before considering the benefits in terms of noise and air pollution reduction. The idea of congestion pricing then “circled the table” for nearly 40 years until December 2000 when parliament passed the Transportation Act to empower local authorities in England and Wales to charge for road use. The act also required that revenue from the congestion charge should be used only to improve local transportation over a 10-year planning period (Santos, 2004).

Area and Time

The area charging started on February 17, 2003 in the area of Central London (Figure B-1). The congestion charge zone covers approximately 8.108 square miles (21 km^2) which accounts for only 1.3 % of Greater London. There are 174 entries and exits on the boundary of congestion charge zone. The area charging remains affective from 7 AM to 6 PM, Monday to Friday. There is no charging on weekends, English public holidays and special designated non-charging days. Drivers pay the toll when they cross into or out of the congestion charge zone. Drivers on the boundary ring roads that do not cross the boundary do not pay the charge. There exists a large number of traffic signs in the vicinity of congestion charge zone (Figure B-2) (Santos 2004; TFL 2010).

The charging area (Figure B-1) includes Bayswater, Notting Hill, North and South Kensington, Knightsbridge, Chelsea, Brompton, Belgravia, Pimlico, Victoria, St. James’s, Waterloo, Borough, City of London, Clerkenwell, Finsbury, Holborn, Bloomsbury, Soho, Mayfair and parts of Marylebone (TFL 2009).

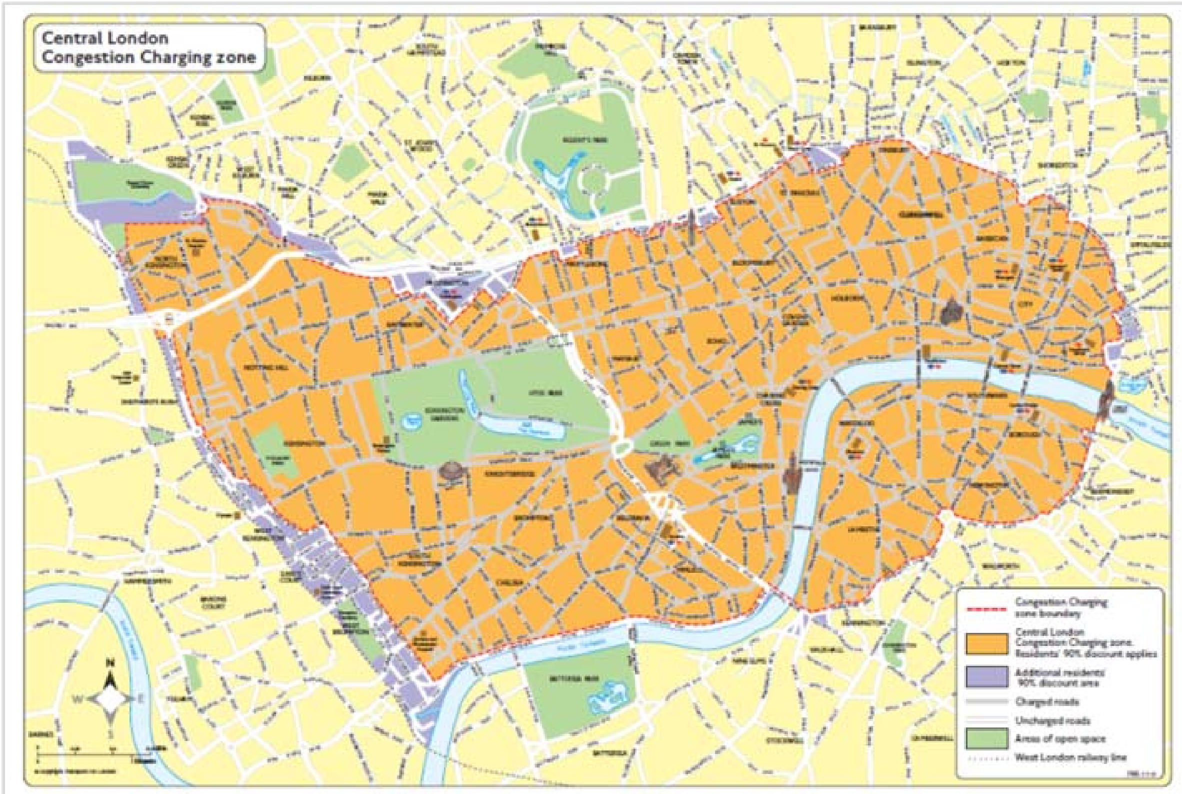

Figure B-1: Central London Charging Zone. Source: (TFL 2007)

Figure B-2: Road Signs associated with London's Congestion Charges ((TFL 2010)

There is no toll booth or barrier at the boundary. Rather, a number of road signs (see Figure B-2) are posted at the boundaries. Approximately 330 cameras are used at the entries and also within the toll area. Color video cameras take wider contextual images of vehicles entering the area while monochrome cameras take close snapshots of license plates. The pictures are linked to an Automatic Number Plate Recognition System (ANPR) so that vehicles entering the area are identified. Records are not kept permanently: by midnight of the day of the plate detection, the records of non-violating vehicles are deleted from the system. Data on violators are forwarded to Evidential Record (ER) for purpose of issuing the Penalty Charge Notice (PCN) (TFL, 2009).

Method of Payment

All road users in the congestion pricing zone are supposed to pay the toll in advance. The system allows payment up to 90 days in advance with discount for advance payment. For trips not paid in advance, payment by midnight of the day of travel can be made without penalty. The daily charge is £8 but increases to £10 if paid by midnight of the following day. The toll can be paid online; by short message service (SMS), phone, automated telephone service; or at the retail store and by post (TFL 2010).

Travelers that fail to pay the toll by the midnight of the following day of system use face a £120 penalty. If the penalty is paid within 14 days, the penalty cost is discounted by 50% to £60. Penalty cost can go up to £185 in case of failure to pay the penalty in within 28 days. Vehicles with three or more outstanding penalty charges may be immobilized or removed anywhere within Greater London. The immobilization fee is £70 and the removal fee is £200 (TFL 2010).

Impact on Traffic and Public Transport

Studies have found that immediately following the toll implementation, the average speed of vehicles in the toll area increased by 21% as the number of vehicles entering the zone reduced by 21% (approximately 710,000 fewer vehicles/day). Based on the assumption that the uncongested network travel rate of London is 1.9 min/Km, the congestion reduced by approximately 30.4%. The traffic on the inner ring road increased, but due to traffic management (more green time to the inner ring roads) the congestion was not significantly increased. The traffic on the main roads across Inner London outside the charging zone did not significantly increase (Santos 2004).

Due to implementation of congestion charge, public transportation increased by 2% increase – a rather low percentage increase that could be explained by the fact that a majority of the travelers coming to inner zone were using transport even before the implementation of congestion charge. After the implementation of congestion charge, it was observed that in the time period 7-10 AM, the number of bus passengers increased by approximately 14,000-15,000. The public transport authority of London added 11,000 extra bus-spaces to serve the increased demand. The increased system capacity resulted in 25% reduction in bus waiting time across Greater London and 33% in the charging zone (Santos 2004).

The use of revenue

A 1999 survey conducted by ROCOL indicated that 67% of people were in favor of spending funds on a varied mix of transport improvements; this percentage increased to 73% when the respondents' spending package preference was introduced. The area charging resulted in total revenue collection of £ 68 million a year in 2003 (Santos 2004) which increased to £137 million a year in 2007/08 (ROCOL Working Group 2000; TFL 2010).

The plan for using collected revenue include (1) bus network improvement, (2) developing tram and high quality bus schedule (3) safety and security improvement scheme (4) road and bridge improvement program and (5) late-night public transport improvement. In medium and long term, this money would also help fund the expansion of underground and rail capacity across London, improvement of rail service, the new Tame gateway river crossing and selected improvement to London's roadway system (ROCOL Working Group 2000; TFL 2003).

Stockholm's Congestion Tax (Area)

Background and History

Stockholm's congestion charge is a tax paid by vehicles that enter or exit central Stockholm, Sweden. The congestion charge was implemented after a seven-month trial period which started on January 3, 2006 and ended on July 31, 2006. During the trial period in the Stockholm central area, travelers had a chance to experience the congestion charges. Before the trial period, major opposition to the project came from commuters who lived outside Stockholm and had to travel to work in central Stockholm. During the trial period, the low charge amount and the resulting reduction in traffic congestion (25%) helped turn the tide of public opinion in favor of the project (STA 2010a; Wikipedia 2010a).

On September 17, 2006, a referendum was held and the Stockholm residents approved the implementation of pricing scheme. The parliament passed the law in June 2007, and the pricing scheme has been permanently implemented since August 1, 2007 (STA 2010a; Wikipedia 2010a).

Charging Area

The Stockholm congestion charge is an area-charging scheme. The cordon boundary covers all central Stockholm area. The control points include Danvikstull, Skansbron, Skanstullsbron, Johanneshovsbron, Liljeholmsbron, Stora Essingen, Lilla Essingen, Fredhäll/Drottningholmsvägen interchange, Lindhagensgatan interchange, Ekelundsbron, Klarastrandsleden, Karlberg/Tomtebodavägen interchange, Solnabron, Norrtull, Roslagsvägen, Gasverksvägen, Lidingövägen and Norra Hamnvägen. (STA 2010a) The toll area and all 18 charging control points are shown in Figure B-3.

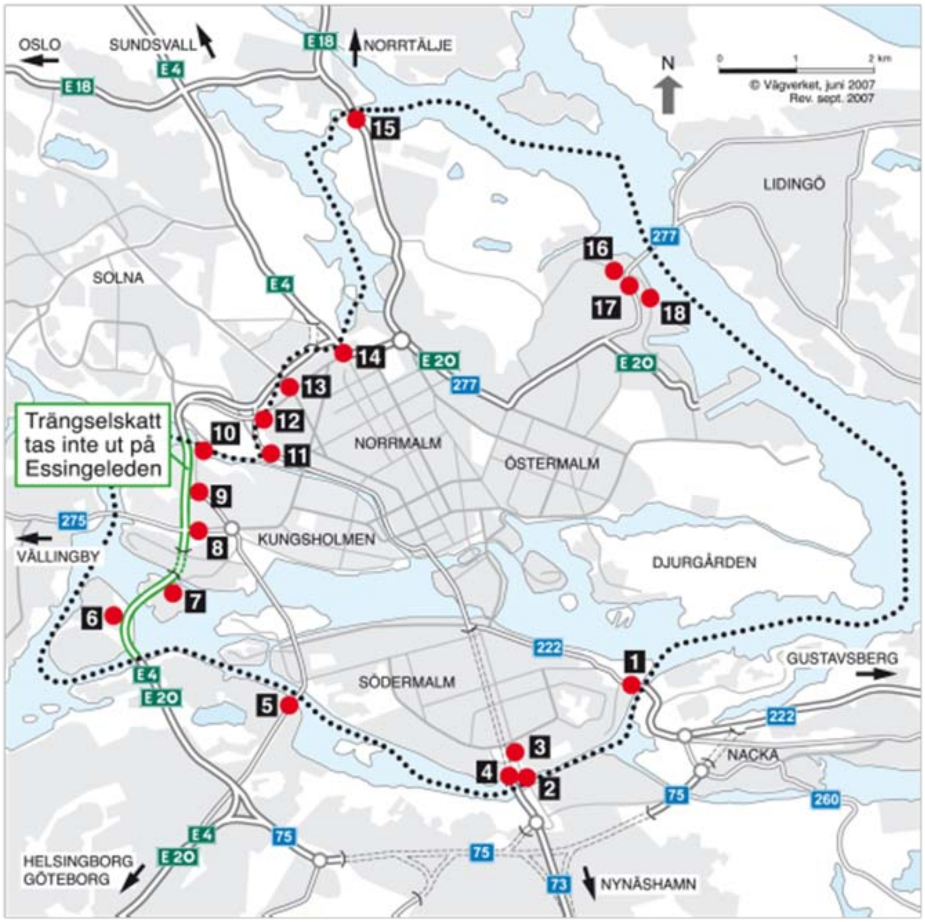

Figure B-3: Stockholm charging area showing the charging control points (STA 2010a)

The Charge Amount

Every vehicle pays the toll for entry into and exit out of the area (i.e., drivers pay every time they cross the cordon line) from Monday to Friday 6:30 AM to 18:30PM. There is no charge on weekends and public holidays. The amount of toll varies depending on time of day. The details of charging schedule are presented in Table B-1 (STA 2010b).

Table B-1: The Stockholm charging schedule (STA 2010b)

Times	Amount
06.30–06.59	SEK 10
07.00–07.29	SEK 15
07.30–08.29	SEK 20
08.30–08.59	SEK 15
09.00–15.29	SEK 10
15.30–15.59	SEK 15
16.00–17.29	SEK 20
17.30–17.59	SEK 15
18.00–18.29	SEK 10
18.30–06.29	SEK 0

Vehicle classes that are exempted from the congestion charge include: emergency vehicles, buses, diplomat-registered vehicles, motorbikes, foreign-registered vehicles, military vehicles, and green cars (STA 2010c).

The Methods of Payment

The congestion pricing scheme in Stockholm is levied as a tax. The congestion fee paid can be used as tax deductible item for both individuals and businesses. Drivers have to register for the use and toll cannot be paid at the entry or exit points of the area. A monthly bill is sent to drivers who submit payments no later than the due date on the slip (STA 2010d). Drivers can choose to pay the bill by transferring money in to the Swedish Transport Agency's account, or setting the automatic transfer option called "Autogiro". The penalty for failing to pay the bill is SEK 500 (STA 2010d).

Enforcement Technology

Since toll is not collected using usual tolling booth, special enforcement technology comprising of video cameras and laser detectors is used to collect the vehicle information (Figure B-4) of defaulters. The video cameras and laser detectors are installed on gantries at all 18 controlling points to detect vehicle passing the cordon line. Whenever a vehicle passes the control points, the laser detector (number 1) initiates the cameras system which captures the front and back picture of the vehicle (number 2 and 3). Optical Character Recognition (OCR)/Automated Number Plate Recognition (ANPR) software are used to read the license plate from vehicle photographs (Roadtraffic-technology.com 2003; STA 2010e).

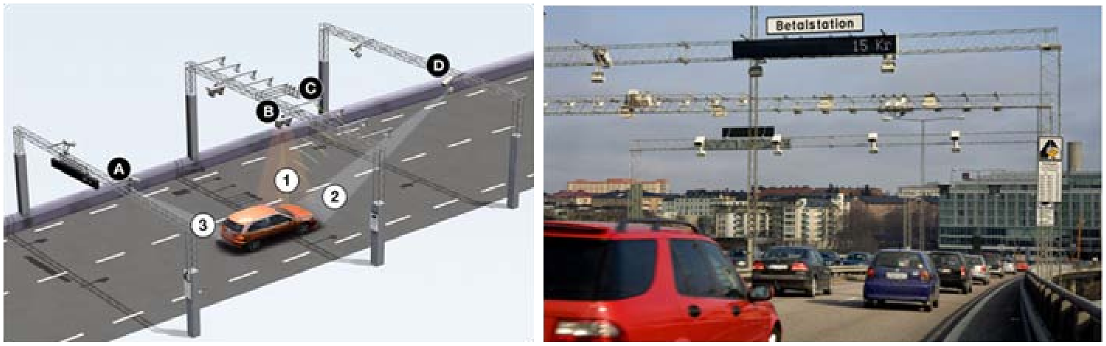

Figure B-4: Tolling control points in the Stockholm charging area (STA 2010e)

Ontario 407 Express Toll Route (407ETR)

Background and History

This project, termed the 407 Express Toll Route (ETR), is a 108-kilometer highway that constitutes one of the 400-series highways bypassing highway 401, one of the busiest highways in North America. The project was initially planned in1960 and finally built by the Ministry of Transport in 1997. The highway was leased to a private consortium in 1999 through a 99-year contract. At that time, the contract was leased for $3.1 billion to a consortium of Canadian, Spanish and Australian operators collectively called 407 International, Inc. At the current time, the highway is valued at over $10 billion. In the original contract, the private company had unlimited control of the highway toll, and the government could not build freeways nearby or potentially compete with Highway 407. However, the government can construct light rail transit to compete with the highway. This contract has been strongly criticized being underpriced and for providing the operator with uncontrolled tolling. On several occasions, these issues have been sent to the law courts. On January 6, 2005, the Supreme Court granted the government to appeal decision on toll (407ETR 2010a; Wikipedia 2010b)

Figure B-5: Toronto’s Highway 407 Express Toll Route (ETR) (407ETR 2010a)

Enforcement Technology

The project is often described as an express toll route (ETR) as there is no toll booth. The video cameras and radio antennas are used to detect vehicles that enter or exit. The system identifies vehicles in two ways (1) the video cameras take photos of vehicle license plates, or (2) the radio antennas communicate with transponders attached in the windshield of vehicles. The users do not need to have transponders as the front and rear images of vehicles are taken when they pass the gantries at the entry and exit points. The system is able to notify the entry and exit locations and times and thus calculates the appropriate toll amount. The images from the video cameras are sent to the ANPR where the license plate numbers are detected and recorded.

The Amount of Toll

The toll amount varies by the time of day, vehicle type and distance travelled in the system. Figure B-6 shows sample charge rates for light vehicles and heavy single-unit vehicles. In addition to toll, drivers without transponders are also required to pay a video-processing fee.

Payment Methods

At the end of every month, the bills are sent out to owners of registered transponders or those whose license plate were detected. Users can pay their bill using any one of several mechanisms: setting pre-authorized payment from bank accounts or credit cards, online payment by credit card or telephone call center. The bill is to be paid within 37 days of the date of issue. Failure to pay may result in invalidation of the vehicle license plate (407ETR 2010b).The company also offers an “exceptional hardship plan” for persons whose outstanding tolls and fees exceed 1,000 dollars (407ETR 2010c).

Light Vehicle	Heavy Single Unit Vehicle	Heavy Multiple Unit Vehicle	Complete Fee Details

Light Vehicle 5000kg & under (registered gross weight) Passenger cars, vans, limos, pickups, sport utility trucks, light duty trucks	Transponder Recorded	Video Recorded
Light Vehicle		
Regular Zone Peak Rate (see map below) Weekdays 6am-10am, 3pm-7pm	21.35¢/km	21.35¢/km
Light Zone Peak Rate (see map below) Weekdays 6am-10am, 3pm-7pm	20.10¢/km	20.10¢/km
Off-Peak Rate Weekdays 10am-3pm, 7pm-6am, Weekends & Holidays	18.35¢/km	18.35¢/km
Monthly Transponder Lease	$2.50*	$0.00
Annual Transponder Lease	$21.50**	$0.00
Monthly Account Fee	$0.00	$2.50
Video Toll Charge	$0.00	$3.60 per Trip
Trip Toll Charge (This is not a per kilometre charge.)	$0.40 per Trip	$0.40 per Trip

IMPORTANT: a $50.00 FLAT TOLL CHARGE PER TRIP is billed to any light vehicles without a transponder whose rear licence plate is not visible to, or recognizable by our toll system.

Light Vehicle	Heavy Single Unit Vehicle	Heavy Multiple Unit Vehicle	Complete Fee Details

Heavy Single Unit Vehicle Over 5000kg (gross weight or registered gross weight)	Transponder Recorded		Video Recorded
Heavy Single Unit Vehicle			
Regular Zone Peak Rate (see map below) Weekdays 6am-10am, 3pm-7pm	42.70¢/km		42.70¢/km
Light Zone Peak Rate (see map below) Weekdays 6am-10am, 3pm-7pm	40.20¢/km		40.20¢/km
Off-Peak Rate Weekdays 10am-3pm, 7pm-6am, Weekends & Holidays	36.70¢/km		36.70¢/km
Monthly Transponder Lease	$2.50*		$0.00
Annual Transponder Lease	$21.50**		$0.00
Monthly Account Fee	$0.00		$2.50
Video Toll Charge	$0.00		$15.00 per Trip
Trip Toll Charge (This is not a per kilometre charge.)	$0.50 per Trip		$0.50 per Trip
Heavy Vehicle Minimum Trip Toll Charge (up to)	Peak	Off-peak	
	$11.00	$10.50	

IMPORTANT: It is mandatory for all heavy vehicles to have a valid transponder. Without a valid transponder, you run the risk of being charged a fine under the Highway Traffic Act.

Figure B-6: Toll rates for light and heavy vehicles, 407 Express Toll Route (407ETR 2010a)

SR 91 Express Lanes, Orange County, California

Background and History

SR-91 is 10-mile toll road located in Orange County, California. It is the 1st application of Congestion Pricing in the U.S. The highway is constructed in the median of SR-91 and connects the orange/riverside counties and Costa Mesa Freeways (SR-55). The purpose is to mitigate congestion between the Riverside and Orange counties.

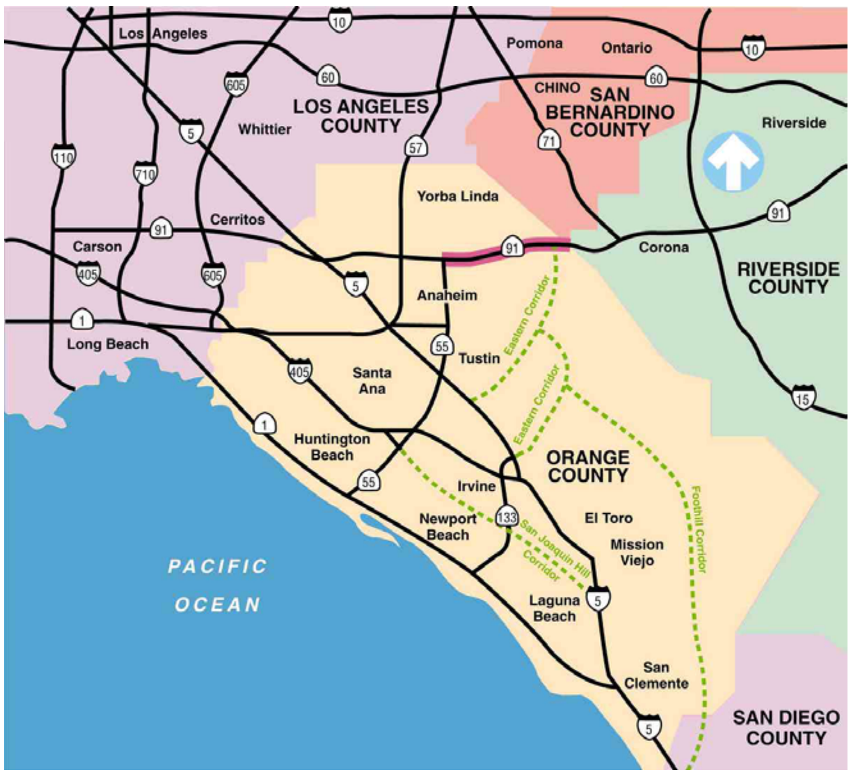

Figure B-7: The SR-91 Express Lanes (CALTRANS, 2010)

The expressway was first opened in December, 1995. It was constructed with a total cost of $135 million through a public private partnership (PPP) between the California Private Transportation Company (CPTC) and the State of California. As per 35-year agreement, the government would not build any competing road in the buffer area of 1.5 miles. Also, improvement of any roadways along the corridor was prohibited. The private company was responsible for the toll collection. As congestion increased, specific clauses in the agreement led to several problems. As a result, in January 2003, the project reverted to the Orange County Authority for $207.5 million to solve these problems (Cantrans 2010a; OCTA 2010a).

Characteristics and Amount of Toll

The 91 Express Lanes has four lanes (two in each direction) separated from main lanes of Riverside Freeway with reflective yellow plastic lane markers. There are two entries only, at either end of the lanes. The express lane helps reduce travel time by 30 minutes on average and helps maintain the free flow speed of the express lanes. The toll amount, which depends on the time of day and occupancy, varies from approximately $1 to $10. Vehicles with over three occupants use the system for free and about half-price during the peak evening rush hour (4-6 PM). To set the toll price, the toll schedule is updated every 6 months. The express lane operates 24 hours a day, 7 days a week.

Drivers have to register and receive transponders before using the system. On each occasion of system use, the appropriate funds are deducted from a pre-paid account. During registration, users can choose from many account plans available, depending on the level of usage. These include the standard plan (for people who use the system between 2- 20 times a week), the 91 Express Club (for people who use the system more than 20 times a week), the Convenience Plan (for occasional users) or the Special Access (for usually travelers with HOV3+, green cars, veterans, or etc.).

Enforcement Technology and Violation

Antennas are used to communicate with the transponders in registered vehicles. The photo license plate technology is use to detected non-registered vehicles. For non-registered vehicles, the toll bill is sent to home of the road user plus additional $20 penalty for the first time of violation, and $35 for the second time. Drivers are given 21 days to settle violation bills.

91 Express Lanes — **Toll Schedule** — Effective April 1, 2010 — **Eastbound** — SR-55 to Riverside Co. Line

	Sun	M	Tu	W	Th	F	Sat
Midnight	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30
1:00 am	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30
2:00 am	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30
3:00 am	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30
4:00 am	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30
5:00 am	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30
6:00 am	$1.30	$2.05	$2.05	$2.05	$2.05	$2.05	$1.30
7:00 am	$1.30	$2.05	$2.05	$2.05	$2.05	$2.05	$1.30
8:00 am	$1.65	$2.05	$2.05	$2.05	$2.05	$2.05	$2.05
9:00 am	$1.65	$2.05	$2.05	$2.05	$2.05	$2.05	$2.05
10:00 am	$2.50	$2.05	$2.05	$2.05	$2.05	$2.05	$2.50
11:00 am	$2.50	$2.05	$2.05	$2.05	$2.05	$2.05	$2.50
Noon	$3.00	$2.05	$2.05	$2.05	$2.05	$3.10	$3.00
1:00 pm	$3.00	$2.85	$2.85	$2.85	$3.10	$4.85	$3.00
2:00 pm	$3.00	$4.05	$4.05	$4.05	$4.15	$3.60	$3.00
3:00 pm	$2.50	$4.35	$3.70	$4.95	$5.90	$10.25	$3.00
4:00 pm	$2.50	$5.55	$7.75	$8.25	$9.90	$9.30	$3.00
5:00 pm	$2.50	$5.35	$7.25	$7.75	$9.05	$7.25	$3.00
6:00 pm	$2.50	$4.35	$4.10	$3.60	$4.90	$5.25	$2.50
7:00 pm	$2.50	$3.10	$3.10	$3.10	$4.45	$4.90	$2.05
8:00 pm	$2.50	$2.05	$2.05	$2.05	$2.85	$4.45	$2.05
9:00 pm	$2.05	$2.05	$2.05	$2.05	$2.05	$2.85	$2.05
10:00 pm	$1.30	$1.30	$1.30	$1.30	$1.30	$2.05	$1.30
11:00 pm	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30

91 Express Lanes — **Toll Schedule** — Effective April 1, 2010 — **Westbound** — Riverside Co. Line to SR-55

	Sun	M	Tu	W	Th	F	Sat
Midnight	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30
1:00 am	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30
2:00 am	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30
3:00 am	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30
4:00 am	$1.30	$2.40	$2.40	$2.40	$2.40	$2.40	$1.30
5:00 am	$1.30	$3.95	$3.95	$3.95	$3.95	$3.80	$1.30
6:00 am	$1.30	$4.05	$4.05	$4.05	$4.05	$3.95	$1.30
7:00 am	$1.30	$4.50	$4.50	$4.50	$4.50	$4.35	$1.75
8:00 am	$1.75	$4.05	$4.05	$4.05	$4.05	$3.95	$2.05
9:00 am	$1.75	$3.25	$3.25	$3.25	$3.25	$3.25	$2.50
10:00 am	$2.50	$2.05	$2.05	$2.05	$2.05	$2.05	$2.50
11:00 am	$2.50	$2.05	$2.05	$2.05	$2.05	$2.05	$2.90
Noon	$2.50	$2.05	$2.05	$2.05	$2.05	$2.05	$2.90
1:00 pm	$2.90	$2.05	$2.05	$2.05	$2.05	$2.05	$2.90
2:00 pm	$2.90	$2.05	$2.05	$2.05	$2.05	$2.05	$2.90
3:00 pm	$2.90	$2.05	$2.05	$2.05	$2.05	$2.50	$2.90
4:00 pm	$3.05	$2.05	$2.05	$2.05	$2.05	$2.50	$3.05
5:00 pm	$3.05	$2.05	$2.05	$2.05	$2.05	$2.50	$3.05
6:00 pm	$3.05	$2.05	$2.05	$2.05	$2.05	$3.00	$2.50
7:00 pm	$2.50	$1.30	$1.30	$1.30	$1.30	$2.05	$2.05
8:00 pm	$2.50	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30
9:00 pm	$2.50	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30
10:00 pm	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30
11:00 pm	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30	$1.30

Figure B-8: Toll schedule effective on April 1, 2010 for SR-91 Express Lanes, Orange County, California, (91-EL, 2010b)

I-15 Express Lanes, San Diego, California

Background and History

The I-15 Express Lanes were first opened in 1988 as HOV lanes. In 1991, the SOV operation was also allowed along with the HOV with a toll for road use. The revenue was used to fund public transit along the corridor. The 1st phase of the pricing program began in 1996. The I-15 Express Lanes are open to both single-occupancy vehicles (SOV) and HOV. The SOVs were made to purchase window stickers and had unlimited access to the facility. In 1997, the window sticker system was converted to electronic transponders. The 2nd phase of the pricing program began in 1998. The toll was made to vary by time of day, and express buses were provided to run between Northern suburb and downtown of San Diego along the I-15.

At the current time, a 1.3-billion construction plan is in progress. Upon completion, the road will be upgraded to 20 miles and 4 reversible lanes. The system uses the removable barrier to ensure efficient traffic management; 3 lanes in the peak-direction and 1 lane in the off-direction. The project plans to have (possibly) 5 access points using a direct access ramp. The system will also have a Bus Rapid Transit (BRT) operating along the line.

The I-15 express lanes are located between the SR-163 and SR-78 (Figure B-9). The project construction is divided into three construction phases as shown in Figure B-9. As at the time of reporting, eight miles of middle part was open to traffic. The North and South parts are scheduled to be fully opened to traffic in 2011 and 2012, respectively (SANDAG, 2010).

Figure B-9: The I-15 Express Lanes, (SANDAG 2010)

Characteristics and Toll Amount

Drivers can use the system by registering and obtaining the “FASTRAK” transponder. The toll amount is deducted from the prepaid account of the FASTRAK of each individual road user. The toll amount can vary from $0.5 to $8 depending on the usage (distance travelled) and the time of day. The toll is adjusted every 6 minutes to ensure that the traffic level of service does not deteriorate to a level below LOS C. The transponder communicates with the antenna at the entry and exits to record the distance of usage. The single-occupancy vehicle pays full price while transit riders, carpools, vanpools, motorcycles, and permitted clean air vehicles are often not charged for travel on the Express Lanes.