International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:13, No:7, 2019

Investigating the Effective Parameters in Determining the Type of Traffic Congestion Pricing Schemes in Urban Streets

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Abstract**—**Traffic congestion pricing – as a strategy in travel demand management in urban areas to reduce traffic congestion, air pollution and noise pollution – has drawn many attentions towards itself. Unlike the satisfying findings in this method, there are still problems in determining the best functional congestion pricing scheme with regard to the situation. The so-called problems in this process will result in further complications and even the scheme failure. That is why having proper knowledge of the significance of congestion pricing schemes and the effective factors in choosing them can lead to the success of this strategy. In this study, first, a variety of traffic congestion pricing schemes and their components are introduced; then, their functional usage is discussed. Next, by analyzing and comparing the barriers, limitations and advantages, the selection criteria of pricing schemes are described. The results, accordingly, show that the selection of the best scheme depends on various parameters. Finally, based on examining the effective parameters, it is concluded that the implementation of area-based schemes (cordon and zonal) has been more successful in non-diversion of traffic. That is considering the topology of the cities and the fact that traffic congestion is often created in the city centers, area-based schemes would be notably functional and appropriate.

Keywords**—**Congestion pricing, demand management, flat toll, variable toll.

I. Introduction

TODAY, most urban environments are affected by high traffic, air pollution and noise pollution, and as a result of these cases, huge sums are spent annually. With the loss of people's time in traffic and the excessive consumption of fuel in the queues and the environmental impacts of annual traffic factors, the economies of societies are damaging. Thus, congestion pricing schemes through demand management is able to solve these traffic congestion and biomass problems. The aim of this scheme is to receive the cost from a part of the network, and in contrast, to spend its revenues for measures to reduce congestion and improve environmental problems, both in infrastructure building and in improving the quality of urban life. Travelers usually do not take into account costs such as the cost of congestion or pollution, as well as the likelihood of an increase in crashes that could be caused by their arrival in the transportation network. For this reason, the marginal cost theory is expressed in such a way that users of the network pay a cost equal to the difference between the marginal social cost and the marginal private cost as a toll. This idea is known as the first-best method, which, of course, its implementation causes a great public protest in society, and as a result, urban policy-makers do not have much desire to implement it. In practice, there are also many constraints and costs for setting up a system for collecting tolls in all areas to fully cover the network. For this reason, the second-best pricing method is the proposed, in which only part of the network includes tolls. This type of pricing has become more relevant because it includes a part of road network and is more accepted by the community.

There are a number of schemes on how to implement congestion pricing schemes, which we will introduce these schemes and investigate their characters in the following. After describing the main features of congestion pricing schemes, planners and decision makers face the main difficulty in determining the type of schemes (if any) that is the best in the specified conditions. Most studies, rather than a selection among the existing schemes, have focused more on the design of a particular type of congestion pricing scheme, but this study analyzes the parameters that are important in determining the appropriate schemes.

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II. Evaluation of Various Pricing Schemes

Pricing schemes are categorized in various ways which can be summarized as follows:

1. Infrastructure-based projects,
2. Cordons,
3. Zonal schemes,
4. Distance-based schemes
5. Combined schemes

In the following, we investigate these schemes and describe their characteristics.

A. Facility-Based Schemes

For many years, tolls have been imposed on roads, bridges and tunnels, and this is still the most common form of pricing on roads. In this way, some network facilities such as freeways, some bridges or tunnels are priced. These types of facilities often have a specific position on the network, which, with pricing on them, control congestion will be possible. In other cases, pricing is for the purpose of financing. Tolls can be imposed on all lines of a road or in some lines, such as the routs with the High occupancy tolls (HOT). Also, Tolls can be taken at one point of that facility or at a few points. For

International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:13, No:7, 2019

example, tolls on the Toronto Highway 407, as well as the I-15 Express Line of San Diego, USA (Fig. 1), which were reopened in 2009, are of this type [1].

Fig. 1 Express Line I-15 San Diego [1]

B. Cordons

The toll on cordons is one of the district-based pricing forms in which vehicles pay tolls for the crossing of a cordon to enter or exit, or possibly in both directions. A cordon scheme can include several cordons, and it can include sidelines to control rotational motion around the area. All available schemes are seamless cordons. Norway's toll rings were the first cordons that were created, but their goal was to make money, not to reduce congestion.

According to Eliasson's study, only the cordon scheme designed to manage the congestion is the Stockholm city toll scheme with 18 control points that has surrounded the city center cordon (Fig. 2). Daily entry tolls are up to $ 47.8 a day on working days from 6:30 AM to 6:30 PM, with a toll of $ 1.41, $ 2.12, or $ 2.828 depending on the time of a day. No tolls are collected on weekends, holidays and one day before the holidays [2].

C. Zonal Schemes

With a zonal scheme, vehicles pay a cost for entering or leaving the area or for traveling within the area without crossing the border. The boundaries of the area can be attributed to the natural features of the region, such as rivers, lakes and mountains, as well as elements made such as roads, tunnels, residential areas, etc. The only functional areas of this type are the London and New York congestion toll schemes. According to Litman's study, the London scheme began in 2003. The region under the toll composes of a 21 km^2 area around the city center of London (Fig. 3). Flat tolls were set at 5 Euros for driving anywhere in the area or for parking on public roads for working days from 7 am to 6.30 pm. In 2007, the toll increased to 8 Euros and the area with tolls expanded to the west. The journey along the boundary of the area is free from toll. Several groups of vehicles are also exempted from payment, and residents of the priced area are also discounted at 90% [3].

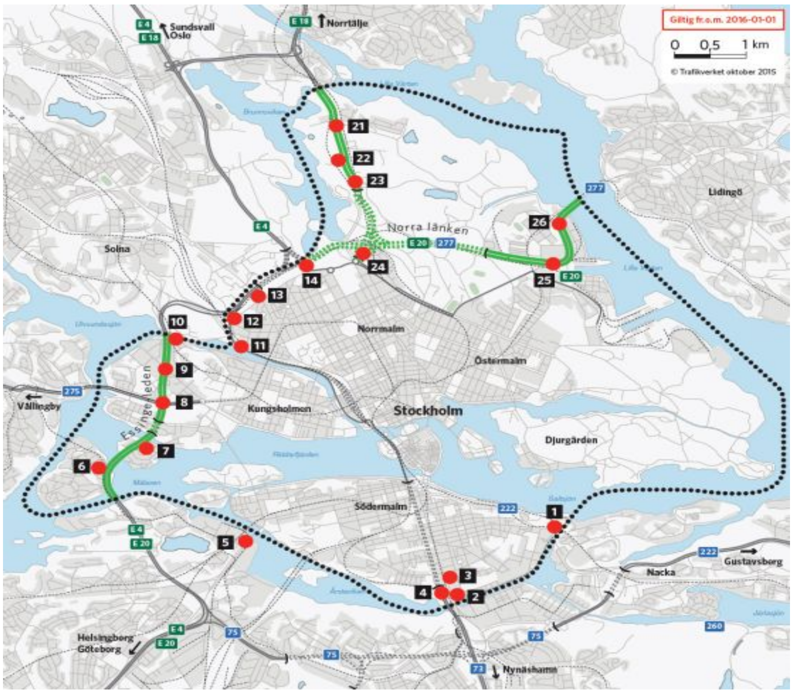

Fig. 2 Pricing belt in Stockholm, Sweden [2]

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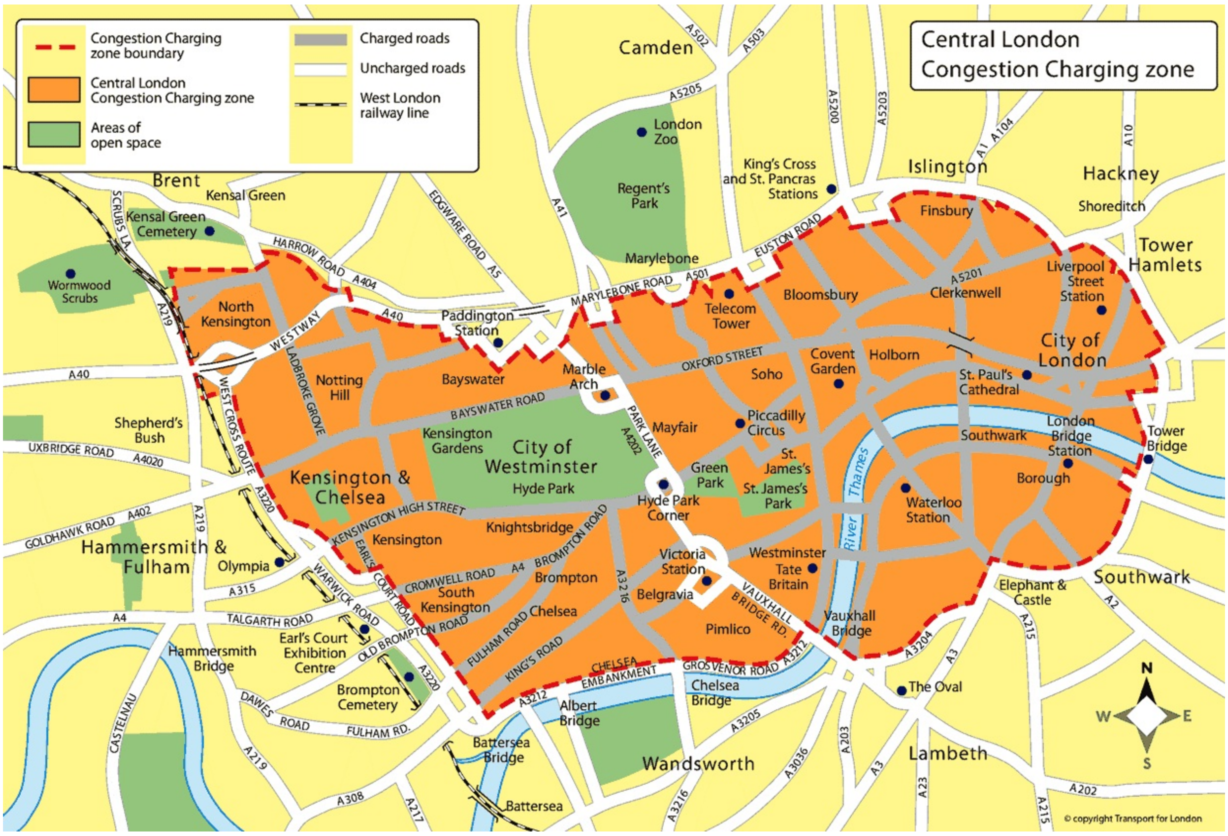

Fig. 3 Pricing area at the center of London [3]

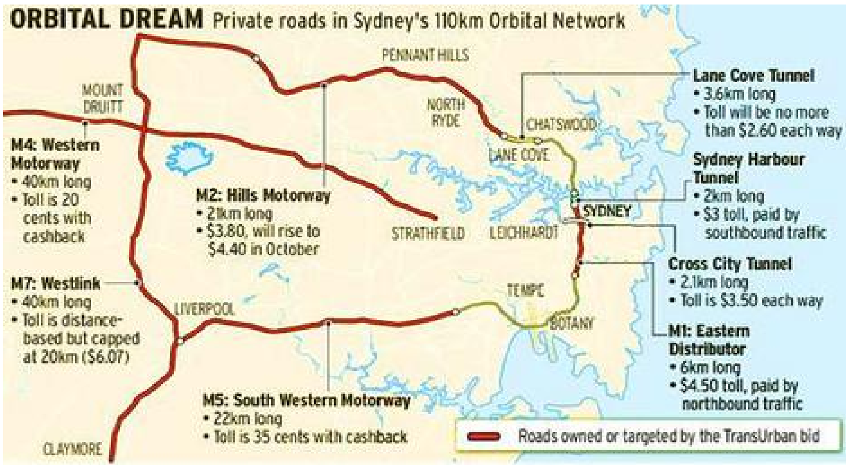

Fig. 4 The Westlink M7 distance-based toll road in Sydney [4]

D.Distance-Based Schemes

With distance-based scheme, the toll will be changed with the distance traveled whether it is linear or non-linear. In this scheme, the lane lines for trucks, as well as networks with high occupancy toll (HOT) are considered, and it is better to impose the tolls on these networks in terms of distance. For schemes that include roads or numerous areas, the rate of tolls may vary depending on the type of road. For example, the Sydney motorway M7, The Westlink M7 is a 40-km toll road connecting Sydney's north and west (Fig. 4). It was Sydney's first distance-based toll road, opened on 16 December 2005. According to a Conway study (2009), four US states have implemented distance-based or weight-based tolls for heavy-goods vehicles (HGVs), but intended pricings are to offset the infrastructure costs imposed on heavy vehicles not to manage demand and congestion; tolls on heavy goods vehicles is implemented in Switzerland, Austria, Germany and several European developing countries [4].

E. Combined Schemes

In this way, two or more schemes of the above schemes are applied simultaneously to the network. The Singapore's Electronic Road Pricing (ERP), launched in 1998, is a hybrid scheme that covers some highways and arterial roads as well as three Cordon- Based District (CBD) and cordon (Fig. 5). Therefore, this scheme is a combination of facility-based and cordon- based tolls. Duration of Toll collection is from 7:00 to 10:00 AM and from 12:00 to 8:00 PM for the CBD and Cordon. But, it is different for highways and arteries, such that tolls change in just 30 minutes, and like the Stockholm scheme, toll payment is necessary for every pass or any entry [5].

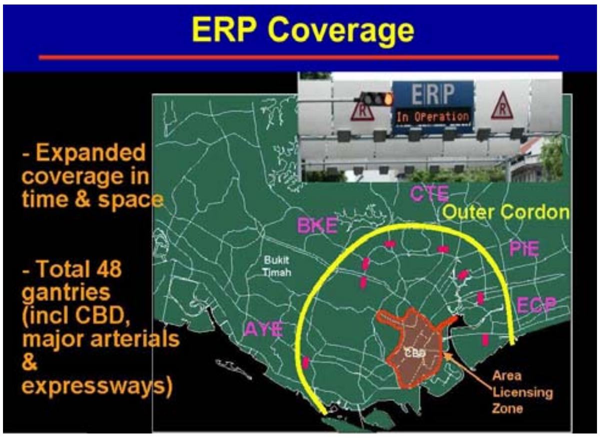

Fig. 5 Road pricing in Singapore [5]

III. Difference in Time and Cost of Tolls in Schemes

A. Time Difference

Pricing schemes in general and road tolls in particular - can be considered as flat, scheduled, or responsive tolls:

Flat tolls are constant over time. In the past, in most of the facilities due to technological and executive problems in pricing, tolls were fixed and unchanged. In some pricing schemes, tolls were available throughout the 24-hour period and in some others, such as congestion pricing in London, tolls are collected with a fixed rate and all working days long, and in other days it is generally inactive [3]. Scheduled tolls change over a day, days of the week, and during the season according to the predetermined schedule. Some examples include some facilities with HOT lines in U.S.A, electronic pricing for Singapore roads and Stockholm urban congestion tolls. The time intervals between changes in tolls vary throughout the scheme, and in some cases, the time interval set in a scheme varies over a day [5]. Responsive tolls in real time or near real-time change as a function of dominant traffic conditions. A number of HOT lines, in which the tolls are adjusted to maintain free flow speed, are only responsive pricing examples. Responsive tolls are reactive, which means they (with a short delay) are set as a function of the current congestion levels. The stage after the responsive pricing in complex conditions is the implementation of a congestion prediction-based scheme. Dong et al. (2007), by developing an algorithm for prediction- based pricing on a road with HOT lines, showed that these types of pricing could predict disturbance in flow and maintain the flow in a better position than responsive pricing [6]. Prediction-based pricing as a tool in traffic management, tracks and predicts the traffic for a long-time. But information, communications, and computing requirements remain a challenge in the scheme.

B. Differences in the Toll Prices

Theoretically, the optimal congestion pricing is a pricing that its tolls vary in different situations during a day. Differences in tolls are more common due to the type of vehicle, number of axles and their weights. However, these features of a vehicle related to the outflow of the congestion imposed by a vehicle are insufficient because the outflow of congestion is related both to the features of a road and to users behavior in the road. Due to the lack of information, the difference in tolls related to the speed and other hazardous behavior during driving was impossible, but recently due to technological advances in the field of computers installed on vehicles, making such differences in tolls is possible and practical. Toll discounts and exemptions for certain groups of vehicles and drivers are also quite common. Different groups in London and Stockholm are exempted from congestion tolls. For example, in London, 90% discount is given to residents within the scheme and 12.5% off to the public transport fleet, as well as various discounts for monthly and annual payments [3]. Discounts are offered as a way to increase revenues and in some cases to make public acceptance.

IV. Analyzing the Important Parameters in Determining the Type of Scheme

After describing the main features of congestion pricing schemes, determining the type of scheme (if any) that is best in the specified conditions is a major problem. Most of the studies have focused on the design of a congestion pricing scheme rather than the selection among the existing schemes, but this study analyzes the effective parameters in determining the type of an appropriate scheme.

Here, attention is focused on choosing a scheme from infrastructure-based and district-based schemes (cordons and zonal schemes). There are various factors in the selection of pricing schemes that analyze the three important parameters of traffic diversion, coverage, and topology of cities.

A. Time and Spatial Diversion of Traffic

The most important issue to consider is whether a scheme can realize the reduction of congestion based on the location and time it occurs, without causing excessive traffic diversions in location and time. Theoretically, route-based congestion tolls are optimal when all routes have toll and tolls can be freely changed by routes, time of day, types of vehicles and other related items. Under these conditions, a pricing scheme based on facility conditions with individualized and optimized tolls for each route from the network will be an optimized scheme. But in practice, comprehensive and widespread toll collection is unlikely to be possible.

The traffic diversion depends on the convenience of access to alternative roads which are free from paying the toll. According to Swan (2008), redirection options are limited in some cities in the United States, such as Boston, San Francisco, Seattle, as in Stockholm, Sweden. Therefore, traffic diversion is an important problem on some roads with tolls [7]. Experiences vary in the case of pricing scheme for heavy goods vehicles (HGV) in Europe. According to Sorensen and Taylor, traffic diversion in Austria where tolls only are collected in main roads, is more than one simple problem than Switzerland where toll is collected on all its roads. In Germany, the tolls on heavy goods vehicles (HGVs) are limited to federal highways and some secondary roads, but traffic diversion has been minimized, since not only potential alternative routes are closed on trucks but also they are considerably low [8]. Therefore, for specific roads or networks, small-scale roads, district-based pricing schemes, in contrast to facility-based pricing, have the advantage of stopping more trips and generally are less susceptible to traffic diversion, so that one of the brilliant tips in London scheme is that there is no increase in the traffic of roads around the area. In addition, the London and Stockholm schemes also seem to be economically profitable.

B. Coverage and Network Domain

The coverage and domain of the network for the difference in tolls are key determinants and key factors in performing pricing schemes based on facilities are as good as possible. The tolls on the high occupancy toll (HOT) lines are the smallest scale available for this category of congestion pricing schemes. Tolls are only imposed on a part of the capacity of a road, and the high occupancy vehicles are exempted from payment. Therefore, passengers can avoid paying tolls by car sharing, as well as using toll-free lines or choosing another route, if available.

Simplified models with two parallel paths and the same users (such as the Weirov 1996 model) show that the maximum potential benefits resulting from congestion pricing are relatively modest unless the toll can be collected from the maximum capacity of the road. When the drivers' heterogeneity is taken into account, economic indicators are somewhat improved [9]. When the travel time value is taken into account, economic indicators will further improve [9]. According to De Palama, the first-best pricing efficiency can be increased by collecting tolls from partial network in the form of scheduled tolls to flat tolls, because variable tolls reduce social costs of trips and the amount of traffic diversion toward paths free from tolls over time besides reducing the congestion [10].

May et al. calculated the optimal congestion tolls on the Edinburgh Road Network for a number of priced paths (n), assuming that we can freely select a set of priced paths for each n. They found that the benefits from collecting tolls increase by reducing the number (n), and concluded that less than 10% of the paths require reaching about 60-70% of first-best pricing advantages [11]. This conclusion contrasts with the examples of two parallel networks mentioned above. So that in comparison to one path, the benefits of collecting tolls on both paths hardly increased. Differences in the results reveal the difficulty in inference of general conclusion about the utility of congestion pricing on the network. In addition to not being able to target congestion in a part of the network, partial tolls also have another disadvantage that exacerbates the congestion in the path free from tolls, and if these routes are made of lower standards than those with tolls, it reduces the safety and damages to the infrastructure.

C. Topology of Cities

Urban topology is the same as urban geography. Understanding the topological characteristics of cities (such as time, position, size, shape, function, morphology, population, internal organization of cities and socio-economic factors within cities) is an important factor in successful implementation of congestion pricing schemes in urban roads. One of the reasons for the good performance of congestion pricing scheme in the city of Stockholm is that the city is built on islands and only 18 access points are enough to form a cordon. In urban areas without natural boundaries, it is very difficult to select the number of cordons and determine their location. May et al. evaluated various cordon options for the City of London where the number of cordons with tolls for movement and radial boundary lines is different. They found the best-performing option (included three cordons, four border lines and tolls in two directions), which its efficiency is several times the yield of a single-cordon option [11]. The best single cordon also has a poor performance because it imposes the same toll on all journeys and allows many journeys to escape from paying tolls. This shows how the difference between cities in terms of topology (as well as other factors such as population, size and public transportation services) affects the parameters of the schemes. Access to high-quality public transportation can also be a prerequisite for the impact of congestion pricing. However, the price increase also has an impact. In both cities of Singapore and London, the tolls are relatively high. In contrast, the low tolls showed little effect.

Zonal schemes have the same advantages and disadvantages of cordon schemes. Areas outside of the schemes must pay tolls for the entry into the area. Tolls are independent of distance and very short journeys with zero tolls are in the priority. The choice between cordon schemes and zonal schemes has not been thoroughly studied, and there are limited practical examples for it. London and Stockholm schemes are the only large-scale examples for each of these schemes designed for congestion pricing.

Another important point is that whether the district- based schemes implemented in Europe will also works in the United States. Will it be effective? Various people, such as Richardson and Bae, searched to answer this question and their overall assessment was negative; it is because in America, compared to Europe, congestion is less concentrated in the city centers and more common on highways. With the exception of New York City, no metropolitan area in the United States experienced an intense congestion as in London.

The dispersal of urban centers and travel chains will undermine public transport, which is a good alternative to driving in the United States. In the United States, public requests for non-toll routs are much more than Europe, and this creates an obstacle to zonal pricing, instead of pricing for certain and selected routes [12].

V. Selecting the Type of Toll and Determining the Amount of Time Change

For each of the pricing schemes discussed in the previous section, there is a choice between flat, scheduled and responsive tolls. It is often claimed that flat tolls are appropriate for maximizing income, while scheduled tolls or responsive tolls are more appropriate for controlling congestion. The reality is not 100%. In order to maximize the income, toll road operators usually tend to have a variable toll pricing policy i.e. they change the toll charge at different times (tolls in the peak time often is less flexible than non-peak time); therefore, maximizes the price to its maximum profit. In the case of London, the speed of travel in the center of the city was fairly constant before commencing toll collecting. While by collecting toll, social welfare conditions have improved somewhat over the duration of toll collecting [3]. Generally, for congestion pricing in most situations, scheduled tolls or responsive toll are more acceptable.

If scheduled tolls are chosen, the scheduling of the tolls will be determined by the amount of toll at each time step and time intervals between the steps. Most of analytical studies are based on the assumption that schedules are chosen so that the second-best scheme is optimal, in other words, to maximize the welfare parameter relative to the constraints imposed. According to Chew, a relatively realistic case study is Singapore's example, in which scheduling of tolls will be adjusted every three months, on June and December, to maintain the speed at least 85% of time on the highway and arterial routes [12]. On route 91-SR, tolls are adjusted using traffic volume information to maintain free flow conditions in high-speed lines without reducing capacity, and conditions in normal lines and other lines in the network of roads are not considered. The distance between the stages of tolls varies across schemes. It is one hour at 91- SR, and 30, 60 and 90 minutes in Stockholm during peak time, and longer in the middle of the day. In Singapore, the tolls generally change every thirty minutes. It may be hard to remember short-interval schedules, but they have this advantage that the tolls change with short time amount between the stages, and drivers have less incentives to accelerate or slowdown their speed in order to pay lower tolls. That's why in 2003 Singapore offered rates that changed every 5 minutes between some half-hour intervals [13].

According to De Palama, responsive tolls has only been implemented on the toll lines for single-seat vehicles in HOT lines such as the 15-S San Diego and 394-I in the city of Minneapolis, USA, and aims at maintaining the free flow speed, maximizes the use of the lines with tolls. In 15-I, the tolls are consistently adjusted every 6 minutes and at 394-I every 3 minutes. Responsive pricing has the advantage that the toll can be adjusted according to the actual travel conditions [14]. Therefore, if an accident blocks a line of multi-way highways, responsive tolls can increase the burden for limiting the number of drivers entering it during the disruption period. Responsive tolls have worked well on the HOT lines, and it may be feasible on distinct routs in which all-available capacities are priced; however, there are some considerations: first, responsive tolls are not likely to be appropriate for district-based schemes, unless public transportation and other driving alternatives have enough capacity to transport passengers who do not want to pay high tolls. Second, responsive tolls can only be effective if passengers are well-informed about them before their implementation to be able change their travel decisions.

VI. Conclusion

Traffic Congestion pricing in urban streets is one of the suitable options for solving traffic problems and air and noise pollution in the cities of the country. Of course, the implementation of pricing schemes requires very detailed studies and planning; one of the important parts of that is to determine the type of pricing schemes. So that it should be selected according to the existing conditions from the infrastructure-based schemes to the appropriate project area. Therefore, considering three important factors of traffic diversion, network coverage and city topology, these points can be noted: Infrastructure-based schemes will divert traffic to other routes, which will reduce their congestion and reduce safety, unless there is a good alternative road, and as the pricing experience in the world has shown, implementation of cordon and district-based schemes has been more successful in non-diversion of traffic. Considering the topology of our cities and considering that traffic congestion is often created in city centers, district-based schemes will be more appropriate. However, it is possible some of the most congested routes to be separately and selectively priced. Another important factor in determining the success of schemes is the existence of a strong public transport system. Also, scheduling tolls are more appropriate in determining the type of tolls, because they are more suitable for reducing congestion and increasing revenues than flat tolls, and do not need the technological facilities and the high cost of implementing responsive tolls. Schedules should also be chosen so that the pricing scheme is optimized to maximize the welfare parameter over the limits imposed.

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