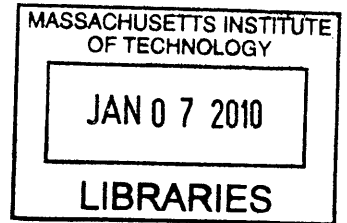


Policies for Parking Pricing Derived from a Queuing Perspective

by

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Submitted to the Engineering Systems Division and the Sloan School of Management
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ABSTRACT

Drivers in urban neighborhoods who cruise streets, seeking inexpensive on-street parking create a significant fraction of measured traffic congestion. The solution to this problem is to reduce the total traffic volume including cruising traffic by implementing a congestion pricing scheme: the imposition of a usage fee on a limited-capacity resource during times of high demand. We review the history of two alternatives for implementing the scheme: road pricing, which involves cordoning off a section of the center city and imposing a fee on all vehicles that enter it; and parking pricing, which increases the costs of on-street and perhaps off-street parking. We find that parking pricing is often a needed companion to road pricing, since in many environments a significant fraction of drivers are simply cruising, looking for inexpensive on-street parking. However, the effectiveness of parking pricing is difficult to analyze quantitatively because vehicles cruising for parking are not clearly distinguishable from other vehicles. We view that the pool of drivers cruising at any time can be modeled as a queue, where ‘queue service’ is the act of parking in a recently vacated parking space and queue discipline is SIRO – Service In Random Order. We develop a queueing model of such driver behavior, allowing impatient drivers to abandon the queue and to settle for expensive off-street parking. We then relate the model to the economic theory of congestion pricing, arguing that price differentials between on-street and off-street parking should be reduced in order to reduce traffic congestion. Using the “Parking Queue” model and collected data, we estimate that less than half of cruising drivers successfully find a vacant spot and the number of cruising vehicles is 10-20% of the total number of parking spaces during peak hours in the most congested area in Boston.

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Chapter 1. Introduction

1.1. Cruising Problem

Many of us may have experienced driving around seeking inexpensive on-street parking in order to avoid pricey parking lots and garages. A recent study of street traffic congestion reveals that excessive number of drivers “cruise” for on-street parking in an urban American neighborhood. This particular report is from the Park Slope section of Brooklyn, New York, a thriving commercial and residential zone (Transportation Alternatives 2007). The purpose of the study was “...to ascertain the extent of the neighborhood’s ever-worsening traffic and parking problems and to propose solutions to both.” Based on data collected early in 2007, “...the study reveals an overwhelming amount of traffic is simply circling the block ‘cruising’ for parking, while the curbside itself is nearly 100% filled with parked vehicles.” The researchers found that 45% of total traffic and 64% of local traffic is cruising for a parking space. And the average curb occupancy rate is 94%, with “...nearly 100% occupancy at metered spaces during peak periods.” This cruising behavior, which can be a major cause of traffic congestion in many neighborhoods, is the focus of our thesis.

1.2. Solution to Cruising Problem

The cruising behavior can be explained as follows: each of us has our own tolerance for delay vs. cost, namely the amount of time we are willing to drive seeking on-street parking vs. the amount of money we would have to pay for off-street parking. Eventually, since “time equals money,” if we are unsuccessful in our cruising for on-street parking, we reluctantly give up the effort and settle for the costly off-street alternative. Therefore, if on-street parking is inexpensive, drivers have strong incentive to cruise. This cruising problem was first pointed out by William Vickrey, Columbia University economist and 1996 Nobel Laureate, in 1954 (Vickrey W. 1954). Shoup studied this issue extensively and proposed various measures in his book “The High Cost of Free Parking” (Shoup D. C. 2005). The solution to this cruising problem is careful management of on-street parking spaces including implementation of various congestion pricing schemes as represented by parking pricing and road pricing.

Parking pricing has been attracting city officials more than road pricing especially after several cities failed to implement road pricing due to difficult political process. For

example, despite the fact that New York City has an extensive public transportation network, New York City's road pricing proposal in 2008 was rejected.¹ In contrast, several parking pricing policies have recently started in major cities such as San Francisco (SF park Project),² Washington D.C. (Performance Parking Project),³ and even New York City (PARK Smart NYC Project).⁴

1.3. Research Questions

Although parking pricing is politically easier to implement than road pricing, planning parking pricing policy is not simple. Transportation authorities need to know the current level of parking-induced traffic, how parking policy affects current traffic, how we should evaluate the effect of the policy, or how much parking price increase should be imposed on drivers in order to suppress parking-induced traffic. These questions are hard to be answered unless we know the mechanism of parking-induced traffic congestion. Without

¹ <http://cityroom.blogs.nytimes.com/2008/04/07/congestion-pricing-plan-is-dead-assembly-speaker-says/?hp> (accessed July 31, 2009)

² <http://www.sfmta.com/cms/psfpark/sfparkindx.htm> (accessed July 31, 2009)

³ http://www.washingtontimes.com/news/2008/apr/21/parking-zones-at-mall-an-asset/?feat=article_related_stories (accessed July 31, 2009)

⁴ <http://www.nyc.gov/html/dot/html/motorist/parksmart.shtml> (accessed July 31, 2009)

having appropriate performance measures and methodology to evaluate the level of parking-induced traffic, it is hard to build and evaluate parking pricing policy.

1.4. Scope of the Thesis

This thesis shows our effort to present a guiding principle for effective parking policy. Specifically, we introduce an analytical method that makes it possible to estimate the number of cruising vehicles that are indistinguishable from other vehicles without conducting extensive intercept survey. We show a simple method to evaluate various properties of parking-induced traffic and estimate appropriate congestion charge we should impose on drivers. Furthermore, analytical forms of our performance measures suggest desirable policy measures to reduce parking-induced traffic, such as controlling parking pricing, time limit, and priority for shorter-time parkers.

1.5. Thesis Structure

The structure of the thesis is as follows: In the second chapter, we compare parking pricing with road pricing and show various successful and failed examples of implementation. In the third chapter, we introduce a queueing model to analyze the cruising behavior of

drivers. Based on the parking queue model introduced in the third chapter, we argue congestion pricing theory in the fourth chapter. In the fifth chapter, we introduce several performance indices for parking-induced traffic congestion, and apply them to evaluate the level of cruising traffic in downtown Boston. Finally, in the sixth chapter, we discuss various measures to reduce parking-induced congestion. The last chapter presents overview of parking policy.

Chapter 2. Parking Pricing and Road Pricing

2.1. Cost of Congestion⁵

As countries develop and the number of cars increases, traffic congestion can impede their cities' development. In the United States, the Texas Transportation Institute (TTI) estimated the annual delay per peak-period traveler in large urban areas with populations of more than 3 million to be 61 hours for the year 2003, which is much larger than 13 hours in small metropolitan areas with populations less than 0.5 million (Schrank D. and Lomax T. 2005). The average annual delay for all cities has grown from 16 hours to 47 hours since 1982. According to TTI's estimate, urban traffic congestion costs Americans \$63.1 billion a year, based only on time and fuel wasted. In general, the total cost of congestion would include at least the following four categories: (1) waste of time: total delays reached 3.7 billion hours in 2003, according to TTI, (2) waste of resources: engines idling in congested traffic wasted 2.3 billion gallons of fuel in 2003, according to TTI, (3) loss of environmental quality, and (4) loss of business. In this thesis, we only consider (1) when we evaluate the cost of cruising. Appropriate parking pricing level estimated in the fifth chapter should be increased if (2), (3), and (4) are included in the evaluation.

⁵ This section is based on the references Downs A. 2004 and May A. D. 2004 Chapter4.

2.2. Congestion Problem as “the Tragedy of the Commons”⁶

To understand how we can solve the congestion problem, we here explain the notion of “the Tragedy of the Commons” introduced by Hardin. This notion is an allegory for a situation in which a free public good is available to the public, each person’s private utility function is optimized by continually incrementally increasing his/her use of that good, and eventually the good become saturated and of limited or no value to anyone. Personal, utility-optimizing decisions are at odds with global societal optima.

To visualize the allegory, consider the Boston Common, where – until the year 1830 – residents of Boston were allowed to graze their cows. This setting could provide an example of the Tragedy of the Commons, if each owner of cows had been persuaded by self-interest to add ‘one more of his cows’ to the Common, each ignoring the deleterious effects of one more cow, until there was no more grass to graze and then no cows could be supported there. This allegory applies to urban street traffic, where the streets of the city correspond to the Commons and cars correspond to grazing cows.

More generally, the Tragedy of the Commons arises if the following three conditions are

⁶ This section is based on the reference Hardin G. 1968.

satisfied: (1) the resource is limited, (2) the resource is shared and open to everyone (i.e., a common-pool resource), and (3) a negative externality exists associated with the usage of the resource.⁷ Like the Boston Commons, the road resource satisfies all these conditions.

In such a case, a “free rider” problem occurs: a driver has little incentive to limit the use of his car because he bears only the fuel and time cost spent on congested roads, and he does not need to bear the external cost, such as the cost of extra congestion or pollution caused by his entrance. Because of the drivers’ free-riding behaviors, the road resource is overused and congestion becomes heavy, which makes the society worse off collectively.

Solutions to the congestion problem are to invalidate at least one of the three conditions listed above. The first approach is to increase the supply if demand is too strong, e.g., add “acreage to the Commons.” This is the strategy that some cities have taken, that is to increase the supply of roads. However, for large cities, adding new roads is difficult because of limited land resources. Even if creating more roads is possible for some cities, it may not solve the problem because more roads attract more traffic in the city, which causes traffic congestion again sooner or later, again with large negative externalities to the city.

⁷ A negative externality is a broader social cost arising from individual decisions, and the individual decision maker does not bear the costs associated with his decision.

In most instances, we cannot solve the “the Tragedy of the Commons” by just increasing the size of “the Commons”. The second approach is to limit the usage of the resource, which can be implemented by various policy measures. The third approach is to incur extra charge for the usage of the resource in order to compensate for a negative externality (Pigou A. C. 1920; Knight F. 1924), which can be realized using either road pricing or parking pricing. In practice, the second and third approaches are generally taken. In the following sections, we discuss the third approach, road pricing and parking pricing, more in detail.

2.3. Road Pricing and Parking Pricing

Continuing the allegory in the previous section, consider a situation in which we charge each farmer with the true total cost of adding his next cow to the Commons. Eventually, this cost becomes so large that the myopic utility maximizing behavior of the farmer changes so he no longer chooses to add more cows to the Common. The same logic can apply to urban car drivers. An economically efficient level of congestion is realized if the negative marginal external cost is imposed to each driver. This can be done by means of either fuel tax or congestion pricing schemes. A fuel tax is not as effective as congestion pricing because it reduces car usage uniformly rather than coping with local and time-

specific forms of congestion. In contrast, congestion pricing (which can be implemented by road pricing and parking pricing) can be applied effectively to specific areas and also made time-dependent if the extra fee, or congestion charge, is adjusted locally and dynamically in accordance with traffic situations. However, the most commonly-used congestion pricing scheme, cordoned-area road pricing, cannot control trips taken within cordoned areas effectively since road users are charged only once per day and residents in cordoned areas are often exempted from paying full congestion charge. Full-scale road pricing, which essentially prices every road in a city, can control traffic level locally and dynamically, but associated administrative costs are large, making it difficult for medium and small-scale cities to implement full-scale road pricing. Singapore's road pricing, with many gantries installed over the city center, is currently the system closest to full-scale road pricing. Hong Kong tested a large-scale, peak-hour pricing system for six months but rejected it because of privacy concerns. A GPS-based system might be a viable solution to address Hong Kong's concerns (Hensher D. A. and Puckett S. M. 2005). One such system has been tried in Gothenburg, Germany, but many technical problems remain before a GPS-based system can be fully implemented.

Parking pricing has the ability to control the driving behavior in the congested area effectively using the price differentials between on-street parking and off-street parking. Parking pricing can be applied locally and dynamically, applied to disconnected, congested areas since parking lots are distributed throughout cities, and adjusted smoothly as congested areas expand or contract without significant investment. The biggest problem with parking pricing is when through traffic is responsible for much of the congestion, since parking pricing cannot impose a congestion charge on each driver if he does not park. In practice, an extensive network of highways services most large cities, and in most cases, drivers with remote destinations rarely enter local congested roads.

2.4. Examples of Road Pricing

Road pricing was first successfully implemented in Singapore in 1975 using a paper license scheme in the form of an area licensing system (ALS). An electronic toll collection system (ERP) using electronic in-vehicle units (IVUs) replaced paper licenses in 1998 to better control traffic (Toh R. S. and Phang S-Y. 1997). A road pricing scheme that is comparable to Singapore's in scale is London's. London's road pricing started in 2003 at an initial

charge of 5 UK pounds⁸ (approximately US\$8) per vehicle per day, which was raised to 8 UK pounds (approximately US\$13) per vehicle per business day in July 2005 (Hensher D. A. and Puckett S. M. 2005). Its charging area has been extended westward since February 2007.

Road pricing schemes implemented in cities other than Singapore and London are much smaller in scale: the level of the charge and the number of toll points are small. Several cities in Norway, Bergen (started in 1986), Oslo (1990), and Trondheim (1991), collect congestion charge (NOK 15 (approximately US\$2) or more)⁹ mostly at toll ring roads for the use of investment on road infrastructure and its maintenance. Durham in U.K. started road pricing in the central area of the city in 2002, with 2 UK pounds (approximately US\$3) congestion charge.

The most recent road pricing scheme is a Stockholm's case, which is controversial among the public: a trial road pricing scheme was applied in Stockholm in January, 2006, and ran for seven months, followed by a referendum. The citizens of Stockholm voted for a

⁸ 1 UK Pound = 1.65 US dollar, as of July 31, 2009

⁹ 1 NOK = 0.16 US dollar, as of July 31, 2009

congestion charging scheme (51.7% in favor, 45.6% against), but majority of residents outside of the charging area opposed to it. The permanent road pricing started in Stockholm on August 1, 2007 following the result of the referendum. Currently, a fee of 10 to 60 kronor (approximately US\$1.4 to US\$8.4)¹⁰ is charged on vehicles entering the inner city using cameras, although drivers were encouraged to install radio-frequency identification (RFID) transponders in their cars.

In contrast to these successful examples, we have seen many failed implementations of road pricing in recent years. For example, Edinburgh's road pricing scheme was rejected in 2005 at a referendum by more than 74% of residents even after the success of London's road pricing (Hu S. and Saleh W. 2005): the plan proposed was to charge 2 UK pounds (approximately US\$3) to enter the cordoned area and 60 UK pounds (approximately US\$100) for violations—amounts much lower than those in London's scheme. The proposal of road pricing in Manchester (2 UK pounds congestion charge) was also defeated by 79% of voters at a referendum in 2008 even though the government promised to support the scheme with 2 billion UK pounds.¹¹ According to the Guardian, U.K. cities including

¹⁰ 1 Swedish kronor = 0.14 US dollar, as of July 31, 2009

¹¹ <http://www.timesonline.co.uk/tol/news/uk/article5330301.ece> (accessed July 31, 2009)

Cambridge, Bristol, and Leeds, which considered implementing road pricing schemes, will abandon their plans.¹²

A proposal for road pricing in New York City backed by Mayor Michael Bloomberg, which would have been the first city to introduce the scheme in the U.S., was rejected¹³ in 2008 because of the strong opposition from various parties. The plan was to charge US\$8 for cars and US\$21 for commercial trucks entering Manhattan below 86th street between 6 a.m. and 6 p.m. on weekdays, or US\$4 for all drivers within the congestion zone.

Many road pricing have failed because of the difficulty in building consensus among all parties with different interests. On the other hand, we have observed many trials of parking pricing recently. We introduce recent examples of parking pricing in the next section.

2.5. Examples of Parking Pricing

Among many cities implementing parking pricing, San Francisco and Chicago are two cities that have a most extensive parking management plan. The city of San Francisco will

¹² <http://www.guardian.co.uk/politics/2008/dec/13/congestion-charging-transport> (accessed July 31, 2009)

¹³ <http://cityroom.blogs.nytimes.com/2008/04/07/congestion-pricing-plan-is-dead-assembly-speaker-says/?hp> (accessed July 31, 2009)

receive \$24.75 million federal funding and start a parking management project called SFpark pilot project. It tries to reduce cruising behavior and to shift the traffic from congested areas to less congested areas by controlling price and availability of 6,435 on-street parking spaces and 11,677 off-street parking spaces managed by the city. Similarly, the city of Chicago was also selected as one of the cities to receive federal funding for tackling traffic congestion.¹⁴ Currently, the cost of traffic congestion in Chicago is estimated to be \$1580 per driver, or \$7.3 billion a year in a wasted fuel and lost time.¹⁵ Chicago will charge \$5 - \$8 charge if the plan is approved (parking pricing plan is still pending now). Parking pricing (congestion charge) has an objective of both smoothing a traffic flow and generating a new revenue stream for Chicago.

Washington D. C. and New York City started parking pricing pilot projects in 2008 on a smaller scale compared to San Francisco. In Washington D.C.,¹⁶ a parking pricing project called “Performance Parking” started as a countermeasure for parking congestion due to

¹⁴ Chicago lost \$153 million grant from the federal government, which was supposed to be used for Bus Rapid Transit System and a parking pricing strategy.
<http://www.transitchicago.com/news/default.aspx?Month=4&Year=2008&Category=&Archive=y&ArticleId=189> (accessed July 31, 2009)

<http://www.chicagobusiness.com/cgi-bin/news.pl?id=32520> (accessed July 31, 2009)

¹⁵<http://www.metroplanning.org/resource.asp?objectID=4473&keyword=moving+at+the+speed> (accessed July 31, 2009)

¹⁶ http://www.washingtontimes.com/news/2008/apr/21/parking-zones-at-mall-an-asset/?feat=article_related_stories (accessed July 31, 2009)

Nationals Stadium opened in 2008. The parking project now returns 80% of its revenue to communities for improving pedestrian/cycling paths and public transit. New York City¹⁷ has started parking pricing pilot project called “Park Smart NYC”, a 6-month pilot project on October, 2008 in Greenwich Village, where 95% of metered parking spaces were occupied before the implementation of the pilot project. Parking price from noon to 4pm (Monday-Friday) is increased from \$1 to \$2. They are considering implementing similar projects in other districts in NY.

The final example we introduce may not be classified as a typical parking pricing scheme. However, the effect of the policy is similar to the effect of eliminating “free” on-street parking: in Tokyo, 2006 revision of the Road Traffic Law enabled private vendors to enforce parking regulations by issuing tickets immediately after identifying violators, without any grace period.¹⁸ With no grace period and improved enforcement, the 15 minutes or more of “free” parking that had been granted drivers on most roads as a grace period has risen to an expensive on-street parking which costs 10,000 Japanese yen

¹⁷ <http://www.nyc.gov/html/dot/html/motorist/parksmart.shtml> (accessed July 31, 2009)

¹⁸ Although on-street parking officially has not been allowed on most roads in Japan, until recently drivers parked almost anywhere because the number of police was insufficient to check for violators. Too, officers permitted a grace period of 15 minutes or more before issuing tickets.

(approximately US\$103)¹⁹ as a penalty fee for parkers. The effect of the policy has been dramatic. According to the Japan National Police Agency,²⁰ three months after Tokyo changed the parking ticket enforcement policy, a 27.2% decrease in the average duration of traffic jams and a 9.5% decrease in average travel time on the main streets of Tokyo were observed. These are comparable to the effects of major road pricing schemes. The agency estimated economic benefits of this policy to be 181 billion yen (approximately US\$1.9 billion) and the reduction in CO₂ emissions to be 15.2 thousand tons/yr. In addition, a modal shift from cars to public transit was observed. In fact, such improvements were observed in not only Tokyo but also in medium-sized cities throughout Japan where parking ticket enforcement was changed.

2.6. Practical Benefits of Parking Pricing

As we have seen above, many parking pricing pilot projects started recently after several cities failed implementing road pricing. These examples demonstrate the proven benefits of parking pricing. In this section, we summarize the practical benefits that parking pricing offers: cost effectiveness, scalability, easy implementation, and flexibility.

¹⁹ 100 Japanese yen = 1.03 US dollar, as of July 31, 2009

²⁰ <http://www.npa.go.jp/koutsuu/shidou30/20060915.pdf> (in Japanese) (accessed July 31, 2009)

(1) Cost effectiveness

Parking pricing controls the traffic flow locally with much less operational cost. Parking pricing does not necessarily require an additional toll-collection organization, making it cost-effective for medium- and small-scale cities for which road pricing may not be affordable. Road pricing usually requires cities to invest on and maintain monitoring system of vehicles entering the center city by cameras (London) or by electronic road pricing gantries (Singapore).

(2) Scalability:

Parking pricing can extend its target area district by district after observing its effectiveness at each stage without costly additional infrastructure or the risk of increasing the fraction of exempted residents, which could significantly reduce the effectiveness of an area licensing road pricing system. For example, many roads in Tokyo are congested not only because of a large inflow from the suburbs but also because of numerous intracity trips: according to one estimate made by the Tokyo Metropolitan Government, about 40% of total trips in Tokyo are intracity trips. A simple single cordon-line ALS would not be effective if

charging area becomes large (Sumalee A., May T., and Shepherd S. 2005). In such a case, parking pricing would be more appropriate than ALS because parking pricing can control traffic locally by varying charges as needed to regulate intracity trips.

(3) Easy implementation:

Parking pricing does not require complex political processes to obtain approval for implementation. Many road pricing schemes failed due to objections from stakeholders or a public referendum. Since road pricing controls the flow of all traffic in the city, the policy affects all businesses, organizations, political parties and residents of the whole city.²¹ Building consensus among all parties with different interests is not easy, as we have seen in Edinburgh and New York City. Road pricing was successfully implemented only at cities where the government or mayor has a strong initiative (Singapore and London) or the level of charge is low (Norwegian cities and Durham).

(4) Flexibility:

Parking pricing is effective at any level of pricing. Even a small increase in parking price reduces cruising-induced traffic effectively, which was observed in Park Smart NYC pilot

²¹ Various issues involving stakeholders are discussed in Farrell S. and Saleh W. (2005).

project in New York. On the other hand, if price increase is large, as we saw in Tokyo's parking policy change (elimination of all short time "free" on-street parking), we could expect a reduction of vehicle usage and a modal shift. In such a case, parking pricing becomes a similar measure to road pricing.

2.7. Incentives to Use Cars

In order to implement pricing measures effectively, it is important to reduce incentives to use cars, such incentives having unintended negative consequences in urban congestion and counteracting the effectiveness of any pricing measures.

One incentive is caused by a large fixed cost for the purchase and maintenance of cars paid in advance and a relatively small usage cost associated with the actual driving. Once they own their cars, car owners want to use cars as often as possible to justify their purchase. To reduce this incentive, one needs to charge more for the usage of cars or to give cash or some other benefit for not using cars. Congestion pricing is an attractive option because it increases the usage cost when cars are used in a congested area. Another example is pay-as-you-drive (PAYD) car insurance. Insurance is often a larger expense than gasoline and

oil expenses for small and intermediate vehicles mostly used for commuting. By changing the insurance system from term-based to distance-based, a fixed cost is decreased and a usage cost is increased, which reduces the incentive to use cars.

A parking benefit offered to commuters by some employers creates another incentive. This benefit is typically free parking at parking garages near their places of work. Employees need to drive to gain the benefit. American firms currently provide 84.8 million free parking spaces to their employees (Downs A. 2004), and some are in the center of large cities. Considering the cost of parking in the centers of the large cities, the benefit of free parking can far exceed daily marginal expenses associated with driving. Census data for the year 2000 show that 35% of government workers in Manhattan drive to work mainly because they have free parking.²² This problem could be solved by employers giving employees the cash equivalent of parking fees to spend on using an alternate mode of transportation. Shoup examined eight case studies conducted from 1993 through 1995 on the effect of a “cash-out” scheme in the Los Angeles region (Shoup D. C. 1997). A cash-out scheme gives employees a choice between free parking and its cash equivalent,

²²<http://query.nytimes.com/gst/fullpage.html?res=9802E3DC1330F931A25752C0A9619C8B63&sec=&spon=&pagewanted=3> (accessed July 31, 2009)

introducing the market mechanism to companies' free parking. This scheme does not remove a benefit from employees since they can either continue driving to work or receive a cash benefit by using public transportation. The results in Los Angeles were remarkable: after a cash-out scheme was introduced, the number of solo drivers fell 17% while the number of carpoolers rose 64%, and public transit ridership increased 50%. The number of miles traveled by private vehicles declined 12%. This program has reduced the number of cars used to commute without sacrificing the number of persons commuting, and according to surveys taken, has increased both employers' and employees' satisfaction. In California, a law was passed in 1992 (although it has not been enforced) requiring all employers to make such cash-out options available to employees (Downs A. 2004).

If the current public transportation is poor, an incentive to use cars in commuting inevitably remains high. The quality of a public transportation system includes its vehicles' speed, punctuality, accessibility, network coverage, cleanliness, and safety. For example, before implementing road pricing, London introduced about 300 additional buses,²³ set new bus routes, and increased the frequencies of bus operation. London also has enforced traffic rules strictly with police cooperation. London currently has 130 km of priority bus lanes,

²³ http://news.bbc.co.uk/2/hi/uk_news/england/2774271.stm (accessed July 31, 2009)

and bus service 24 h/day. Tokyo, too, is famous for its high-quality public transportation system. To compensate for its less than punctual bus system, a GPS bus-locator system has become common in Japan so users can check buses' current location by Internet or cell phone.²⁴ Trains in Japan are reliable and their network is extensive. In contrast, Edinburgh's citizens were generally dissatisfied with their city's public transportation, and as a result, roundly rejected the prospect of road pricing when that was raised. One important difference between London/Tokyo and U.S. cities should be noted: U.S. cities are less densely populated; therefore, providing extensive public transportation in the U.S. is more costly. A park-and-ride system can therefore be especially important in the U.S.

Finally, there is an incentive to cruise if on-street parking is very inexpensive. Two observations²⁵ in New York City have especially interested us: (1) a recent survey conducted by Bruce Schaller, principal of Schaller Consulting, showed that 28% of drivers in the SoHo district in Manhattan were searching for on-street parking,²⁶ and (2) as cited in

²⁴ One example of Japanese bus locator Internet sites is:

<http://info.entetsu.co.jp/navi/pc/location.aspx> (accessed July 31, 2009)

²⁵ Shoup, D. C. (March 29, 2007) Gone Parkin, New York Times Op-Ed.

<http://www.nytimes.com/2007/03/29/opinion/29shoup.html?ex=1332820800&en=cdabf3ece6c4a862&ei=5088&partner=rssnyt&emc=rss> (accessed July 31, 2009)

²⁶ Schaller Consulting (December 14, 2006) Curbing Cars: Shopping, Parking and Pedestrian Space in SoHo Prepared for Transportation Alternatives

http://transalt.org/files/newsroom/reports/soho_curbing_cars.pdf (accessed July 31, 2009)

this thesis' Introduction, a second survey, by Transportation Alternatives, showed 45% of drivers were searching for on-street parking in the Park Slope neighborhood in Brooklyn.²⁷

This, of course, is not always the case, but often is during busy times in city centers, where most drivers try to find a place to park. Historical data on the percentage of traffic cruising shows that between 8% and 74% of traffic may be cruising in search of available street parking in major US cities (Shoup D. C. 2005), with an average time required to find a vacant spot ranging from 3.5 to 14 minutes.²⁸

The underlying problem is inappropriate parking pricing when on-street parking capacity cannot accommodate all who wish to park. For example, in Manhattan, off-street parking (averaging US\$24.42 per person per day) costs 14 times more than on-street parking (which averages US\$1.73 per person per day)²⁹ (Schaller Consulting 2007). If prices for on-street parking are much lower than those charged by off-street parking lots, drivers have a strong incentive to search for parking on the street, creating extra traffic and congestion. When

²⁷ Transportation Alternatives (February 27, 2007) No Vacancy: Park Slope's Parking Problem And How to Fix It

<http://www.transalt.org/campaigns/reclaiming/novacancy.pdf> (accessed July 31, 2009)

²⁸ Shoup, D.C. (2006) Cruising for parking, Transport Policy 13, pp. 479-486.

²⁹ Schaller Consulting (March 1, 2007) Free Parking, Congested Streets.

http://www.transalt.org/campaigns/reclaiming/freeparking_traffictrouble.pdf (accessed July 31, 2009)

congestion is expected, street parking should be eliminated or its price level increased towards that of nearby off-street parking.

2.8. Obstacles to Road Pricing and Parking Pricing

As we saw, pricing schemes such as road pricing and parking pricing are often appropriate for solving road traffic congestion problems in cities. However, although most large cities suffer from congestion, only a handful of cities are successfully implementing pricing schemes. For other cities to implement these schemes successfully, we believe that certain obstacles and potential stumbling blocks must be addressed in the planning process, and that road pricing and parking pricing should be considered in an integrated manner.

i) Fairness issues

There are numerous stakeholders involved with urban transportation. Any change that is viewed as adding costs to transportation will be viewed by some as punitive and unfair, and these groups may then appear as vigorous opponents to any plan that raises prices.

An example is the set of suburbanites who commute to work and who often live where public transportation is inconvenient. They have to bear the full cost of congestion charge since they have no alternative means to commute. On the other hand, urbanites who live near public transportation have an alternative option to commute, so they do not bear the full cost of congestion charge. Hence, suburbanites often regard congestion pricing as a measure that is unfair to them. In order to reduce this sense of unfairness, planners can focus on the following: (1) raising the effectiveness of reducing congestion, (2) using the revenue of congestion pricing for public transportation improvement, and (3) offering suburbanites alternative means of commuting (e.g., share a ride, perhaps with a waiver of the congestion charge).

To raise the effectiveness of reducing congestion, it is important to show that the city is also planning to implement various supplemental measures (such as strict parking regulations, strict traffic rule enforcement, synchronized traffic lights, road repairs/extensions) other than road pricing to solve the congestion problem at the same time. It is also important to raise the congestion charge sufficiently high and limit the

affected time/district in order to guarantee the effectiveness of the scheme and give options for drivers to shift commuting time or detour around the area.

Revenue of congestion pricing should be clearly earmarked for the improvement of public transportation. In addition, it is also important that the current public transportation uses the revenue efficiently. If the public perceives that the current revenue is not well spent, then they are likely to regard congestion pricing as the compensation for inefficient use of the financial spending by the current public transportation. In such a case, people will not support congestion pricing.

For an alternative commuting method, a bus network system is generally recommended, except for U.S. cities. In Asia or in Europe, the bus is a usual transportation means for many people. Extension of a bus network is a relatively inexpensive, but an effective measure to improve public transit accessibility for suburbanites. For example, in London, the current revenue from congestion pricing is mostly used for the improvement of bus transportation. In contrast, in the U.S., since suburban areas are much wider compared to those in Asia and Europe, providing park-and-ride facilities with inexpensive shuttle

bus/commuter train services is more appropriate. The revenue of congestion pricing can be used to build those facilities to give some of the benefit of congestion pricing to suburbanites.

ii) Equity issues

If the public perceives congestion pricing as a discriminatory policy against the poor or the elderly or other disadvantaged groups, then the public -- including public transportation commuters -- may reject the scheme. Hence, it is advisable to conduct a survey to learn of the proportion of low- and moderate - income people who use cars to commute. The results of such a survey will provide guidance to planners on fine-tuning of the congestion pricing plan. Often, the great majority of low-income commuters use public transportation, so the initial concerns about equity can be alleviated by the survey results. For example, a survey conducted³⁰ in 2003 by Schaller Consulting for Transportation Alternatives and the NYPIRG Straphangers Campaign showed that most people who drive into Manhattan are wealthy. Specifically, Schaller Consulting conducted a survey regarding the East River bridges connecting Manhattan with other parts of the city. The East River bridges are

³⁰ Schaller Consulting (September 29, 2003) East River Bridge Tolls: Revenue, Traffic, Mobility and Equity Impacts, report prepared for Transportation Alternatives and NYPIRG Straphangers Campaign: <http://www.straphangers.org/tollreport/tollreport.pdf> (accessed July 31, 2009)

inexpensive or even free, and therefore heavily congested. In order to estimate the effect of congestion charge to drivers crossing the bridges, Schaller Consulting investigated the equity issue and found that lower-income people are far more likely to take public transit than to drive themselves across the bridges. Since drivers crossing the bridges tend to be in the upper income ranges anyway, therefore, Schaller concluded that a toll would have little impact on lower-income drivers.³¹

iii) Concerns for business

Retail business and restaurant business may be negatively affected if the improvement of traffic conditions leads to a net reduction in the number of people entering the city. If retail/restaurant business owners believe this is a risk, then they will form a strong and influential opposition to congestion pricing and try to achieve the political decision to reject any pricing policies that alleviate traffic congestion. Their concern might be legitimate. For example, the London Chamber of Commerce reported in its retail survey published in 2005 that the road pricing scheme in London was negatively affecting retail business.

³¹ The researchers also found that many drivers use free bridges to avoid tolls; free bridges are extremely congested as a result. The congestion mechanism triggered by the price differential resembles the parking pricing problem we are considering here.

According to their report,³² 79% of Central London retailers had experienced a fall in receipts and over half (56%) had seen a drop in number of customers. Forty-two percent of respondents indicated they felt the congestion pricing scheme was all or mostly to blame.

Whether this result in London is a permanent condition is still unknown. At the extreme, there are numerous examples of cities removing vehicular traffic totally from designated “walking mall” areas that then become revitalized with many prosperous shops and restaurants. The absence of congestion, noise and street chaos should make an urban neighborhood more attractive to shoppers and other visitors. The key is to include in any master plan alternative means for such visitors to easily travel to these formerly congested areas. In the case of vehicle-free walking malls, installation of inexpensive off-street parking perhaps with shuttle bus service is an example of a transport alternative. This is an illustration of an instance in which innovative parking pricing results in new lower costs for parking than previously experienced, with elimination of on-street parking and subsidized inexpensive off-street parking.

³² Campaigns Team, London Chamber of Commerce and Industry (January, 2005) *The Third Retail Survey: The Impact of Congestion Charging on the Central London Retail Sector – Eighteen Months On* <http://www.londonchamber.co.uk/docimages/260.pdf> (accessed July 31, 2009)

As in most complex systems, the key is to listen and learn from all stakeholders and to then design a system that is responsive to their major concerns.

Chapter 3. Queueing Model for Parking Pricing

In the following, we develop a model that depicts cruising drivers seeking on-street metered or free parking. We assume that all parking spaces are occupied almost all of the time that would-be parkers are seeking parking spaces. Drivers seeking parking spaces are assumed to be driving around through the streets seeking the first available spot. As soon as one opens up, meaning a parked car is driven away, the next cruising car virtually immediately occupies that spot. The platoon of cruising cars is a moving queue serviced in random order. Not all would-be parkers are served in this queue, as the arrival rate of would-be parkers exceeds the departure rate of parked cars. So, we allow drivers in the cruising queue to become discouraged, leave the queue and presumably settle for more expensive off-street parking (for instance, in a parking garage or in a parking lot).

For modeling purposes we assume an infinitely large homogeneous city with S parking spaces per square mile. We assume that the statistics of parking space availability and desirability are uniform over the city. We assume that the time any given parker occupies a parking space is a random variable W with probability density function $f_W(x)$ and mean $E[W]=1/\mu$. Prospective or would-be parkers appear in a Poisson manner at rate λA /hour, where A is defined to be the size of the area being considered (in sq. mi.). Prospective

parkers will cruise looking for the first available parking space. Any unsuccessful would-be parker can become discouraged. We model this process by assuming that any would-be parker will leave the queue of cruising would-be parkers at an individual Poisson rate of γ/hr .

There are two “large numbers” features in this system that allow us to model the queue as a Markovian system. First, regardless of the details of the probability density function (pdf) $f_W(x)$, the aggregate process of parked cars leaving parking spaces is accurately modeled as a Poisson process with rate $AS\mu/\text{hr}$. This is because the departure process from any given parking space is seen as a renewal process with inter-renewal pdf $f_W(x)$. As is well known, the merger or pooling of a large number of (sufficiently well-behaved) renewal processes converges to a Poisson process (Cox D. R. and Smith W. L. 1954). We assume that the number of parking spaces we are considering is sufficiently large so that this approximation is very accurate. Second, the time until renegeing of any would-be parker could be any well-behaved random variable having mean $1/\gamma$, not necessarily a negative exponential random variable. But, if the moving queue of cruising would-be parkers is sufficiently large, we again have the pooling of many renewal processes --- each having the same probability

density function of time until “renewal” and each starting at a random time. Such pooling will result in the aggregate process of N would-be parkers leaving the queue becoming a Poisson process with rate $N\gamma$, where N is typically large enough so that the Poisson assumption is valid.

We require one additional assumption in order to model this process efficiently. We assume that when there are zero cars cruising in the modeled area, no parked cars leave their spaces. We know that this assumption is incorrect, but we are focusing on large queues of cruising cars in which case the likelihood of zero cruising cars is very small. If this assumption in an application setting is not valid, one can eliminate it by creating a larger Markovian model that includes the possibility of several or even many empty parking spaces.

In our work we will focus on a square area of the city having unit area (e.g., one square mile or one square kilometer). We will assume that this region is large enough for our saturation congestion theory to be valid. One might argue that in any actual city no would-be parker feels constrained to cruise within any arbitrary boundaries. This is true. But for

every would-be parker who starts within our modeled square and then ventures out of it looking for an available parking space, there is statistically an another equivalent would-be parker who started in some near-by zone who ventures into our zone. Statistically, for everyone who leaves, there is someone who enters. We can take care of this by placing “reflecting barriers” around our zone, so that when anyone in the real system leaves, we simply reflect him or her back into the zone, creating a statistical equivalence to the real non-cordoned system.

3.1. The Markov Birth and Death Model

Assuming one square mile of operation, we now can draw the state-rate-transition diagram for this queue, as shown in Figure 3-1.

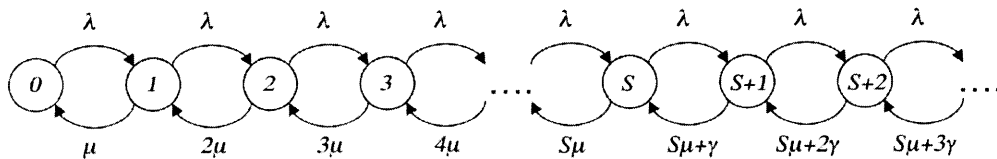


Figure 3-1 State-Rate-Transition Diagram for On-street Parking System

By the usual process of “telescoping” balance of flow equations, we can express each steady state probability P_n in terms of P_0 and a product of upward transition rates (λ 's)

divided by the product of downward transition rates between state n and state 0. The result is

$$P_n = \frac{\lambda^n}{\prod_{i=1}^n (S\mu + i\gamma)} P_0$$

Now, invoking the requirement that the steady state probabilities sum to one, we obtain

$$\left(1 + \sum_{n=1}^{\infty} \frac{\lambda^n}{\prod_{i=1}^n (S\mu + i\gamma)}\right) P_0 = 1,$$

or,

$$P_0 = 1 / \left(1 + \sum_{n=1}^{\infty} \frac{\lambda^n}{\prod_{i=1}^n (S\mu + i\gamma)}\right).$$

Hence,

$$P_n = \frac{\frac{\lambda^n}{\prod_{i=1}^n (S\mu + i\gamma)}}{\left(1 + \sum_{m=1}^{\infty} \frac{\lambda^m}{\prod_{i=1}^m (S\mu + i\gamma)}\right)}, \quad n = 1, 2, 3, \dots$$

For steady state to exist we require $P_0 > 0$, which always occurs. But we want P_0 to be very small for our approximations to be valid.

From the solutions obtained above, we can find all of the quantities of Little's Law, L , L_q , W and W_q . The basic Little's Law relationship is $L = \lambda W$. Here since "the system" is the queue only and service implies finding an empty parking space, we have the equivalences, $L = L_q$ and $W = W_q$. L is the time-average number of cars seeking parking spaces, or equivalently, the mean size of the cruising queue of would-be parkers. W is the mean time that a car remains on cruising, until leaving either by finding a parking space or by frustration and renegeing from the queue.

There are other performance measures of interest. The mean number of parking spaces becoming available per hour is $(1 - P_0)S\mu \approx S\mu$ since $P_0 \ll 1$. The mean number of renegers per hour is $\lambda - (1 - P_0)S\mu \approx \lambda - S\mu$, assuming $\lambda > S\mu$ (which is required for our approximations to be valid). For a random cruising would-be parker, the probability of successfully getting a parking space is $(1 - P_0)S\mu / \lambda \approx S\mu / \lambda$. This agrees with intuition. If say 100 parking spaces become available per hour and 250 would-be parkers arrive each hour, then 40% will succeed in finding a parking space and 60% will leave in frustration.

In the following we will assume that $0 < P_0 \approx 0$. This means that the queue of cruising cars is, for all practical purposes, never empty. Under these conditions, we argue that the mean number of cruising cars is

$$L = L_q = \frac{\lambda - S\mu}{\gamma}$$

This is a fundamental result for our saturated on-street parking system. When the queueing systems is in saturation due to the shortage of the supply of on-street parking, the renegeing rate plays a key role in determining the queue length. We argue its validity by changing the queue discipline from SIRO (Service In Random Order) to LCFS (Last Come, First Served).

It is well known that L and L_q are invariant under the set of queue disciplines whose preferential orderings do not include customer-specific service times. The LCFS discipline is one such discipline. By LCFS here we mean the following: The next available parking space would be given instantaneously to that cruising car that has been cruising for the least amount of time. Usually this car would be the last to have arrived in queue. But it might be the case that the most recent car has already left the queue by renegeing, in which case the next “youngest” cruising car would be selected. The rate of successful parkings per hour is $S\mu$, and thus the fraction of would-be parkers who receive parking spaces virtually

instantaneously upon arrival is $S\mu/\lambda$. The cars that do not get nearly instantaneous parking remain cruising for an amount of time that is exponentially distributed with mean $1/\gamma$. For this revised queueing system W_q , the mean time of cruising can be written,

$$W_q \approx (0)(S\mu/\lambda) + (1/\gamma)(1 - S\mu/\lambda) = \frac{1 - S\mu/\lambda}{\gamma}$$

Since $L_q = \lambda W_q$, we can write

$$L_q \approx \frac{\lambda - S\mu}{\gamma},$$

as was to be shown.

In the above argument we use “approximately equal to” signs instead of “equals signs.”

This is due to the fact that there is a small but positive delay between a car’s arrival in the queue of cruising cars and its selection as a recipient of a parking space. The mean delay between the arrival of a newly cruising car and the emergence of a newly available parking space is $1/S\mu$, assumed to be very small in contrast to $1/\gamma$.

In the following two sections, we model explicitly two alternative ways of implementing

the LCFS queue discipline, as discussed above. These analyses are to show the operational feasibility of the revised but highly fictional LCFS queue discipline. The “real system” at all times is still assumed to follow the SIRO queue discipline.³³

3.2. Random Walk

Assuming the postulated LCFS queue discipline, one can model the arrival of a newly cruising car as an entry into “state 1” an infinite random walk on the non-negative integers, where state 0 implies that the car transitions to a trap state -- signifying successful assignment to a parking space. Transitioning to any higher state $j+1$, $j \geq 1$, indicates that the position in queue has been changed upward from j to $j+1$. Due to the LCFS discipline, higher states imply less likelihood of eventually receiving a parking space. If we define

$$\beta_0 \equiv P\{\text{car enters the trap state}\} =$$

$$P\{\text{car transitions down one state in the random walk}\} =$$

$$P\{\text{car obtains a parking space}\},$$

then we can write

³³ Kaplan derived the same formula $L_q \approx \frac{\lambda - S\mu}{\gamma}$ taking a different approach when analyzing a public housing application queue, in which case a queue discipline is FCFS. (Kaplan E. H. 1988)

$$\beta_0 = P\{\text{first transition is to trap state}\} + (1 - P\{\text{first transition is to trap state}\})\beta_0^2$$

The reason for the term β_0^2 is the fact that if the car has transitioned into state 2, then to be awarded a parking space it must first transition down to state 1 and then eventually to state 0. Each transition down one state occurs with probability β_0 , and the transition processes in each case are independent. The probability that the first transition is to the trap state is equal to the probability that a parking spot becomes available before the next arrival, and that is equal to $S\mu/(S\mu + \lambda)$. Thus we can write,

$$\beta_0 = \frac{S\mu}{S\mu + \lambda} + \frac{\lambda}{S\mu + \lambda} \beta_0^2$$

The solution to this quadratic equation is $\beta_0 = S\mu/\lambda$, and that agrees with our intuition and previous results.

There is a subtlety in the derivation, as the argument appears to ignore renegeing. Since renegeing can occur, the “cars” in the argument are in fact ordered slots: youngest slot in queue, 2nd youngest slot in queue, etc. The car occupant of any slot may change due to renegeing. Once that is seen, the results are seen to be valid, even in the presence of

reneging.

3.3. *Queueing Newly Available Parking Spaces*

If one does not wish to consider the LCFS policy analyzed above, perhaps due to unrealistic demands on tracking newly arriving cars, one can accomplish the same objective by using a queue discipline that we will call **NCNS**, *Next Come, Next Served*. In this scheme each newly available parking slot enters a queue of other newly available parking slots, and this queue is depleted by newly arriving cars seeking parking slots. Any driver in a car lucky enough to arrive when this queue of available parking slots is nonempty is immediately given a parking slot. All others are denied slots forever, and they join the other cruisers who eventually renege after cruising a random time having mean $1/\gamma$. This process can be modeled as an M/M/1 queue, with state i indicating i available parking slots ($i = 0, 1, 2, \dots$), and with upward transition rates $S\mu$ and downward transition rates λ . Since $\lambda > S\mu$, we know that the queue is stable and possesses a steady state solution. Using well-known results from the M/M/1 queue, we immediately have,

$$P\{\text{an empty parking space is available at a random time}\} = 1 - P_0 = S\mu/\lambda < 1.$$

Since Poisson Arrival See Time Averages (PASTA – Wolff R. W. 1982), we have

$$P\{\text{a random arrival obtains a parking space}\} = 1 - P_0 = S\mu/\lambda < 1,$$

as expected.

In steady state, the mean number of free parking spaces is,

$$N_p = \sum_{n=1}^{\infty} nP_n = P_0 \sum_{n=1}^{\infty} n(S\mu/\lambda)^n = \frac{\lambda - S\mu}{\lambda} \sum_{n=1}^{\infty} n(S\mu/\lambda)^n = \frac{S\mu}{\lambda - S\mu}.$$

For example, if $\lambda = 2S\mu$, then $N_p = 1$ free parking space. One free parking space would remain free for an amount of time equal to the time of the next driver seeking a parking space, having mean $1/\lambda$. Usually this time is quite small in contrast other times in the system. More generally, in this instance Little's Law states that $N_p = S\mu W_p$, so we have the mean time that a newly available parking space remains available is

$$W_p = \frac{1}{\lambda - S\mu}.$$

As an example, if $\lambda = 100$ cars per hour and $S\mu = 40$ cars per hour, then $W_p = (1/60)$ hour = 1 minute. Again, this time is small in contrast to other times in the system, and all of our results are correct within acceptable "engineering approximations."

In conclusion, we can feasibly implement a car-to-parking-space queue discipline that supports the equation $L_q \approx \frac{\lambda - S\mu}{\gamma}$, using either LCFS or NCNS. But we remember that the actual or “real” discipline is still assumed to be SIRO.

3.4. *The Distribution of Cruising Cars*

Using the above logic, we see that the entire system, conceptually augmented with either LCFS or NCNS queue discipline, can be viewed as a Poisson arrival queue with infinite number of servers, i.e., an M/G/∞ queue. “Service” occurs for any car the instant the car obtains a parking space or reneges from cruising. The distribution of numbers of cruising cars in the system is not affected by our augmented queueing discipline. Mean service time M can be written,

$$M = (0) \frac{S\mu}{\lambda} + \left(\frac{\lambda - S\mu}{\lambda}\right) \frac{1}{\gamma} = \frac{\lambda - S\mu}{\lambda\gamma}.$$

The Poisson process arrival rate is λ . For the M/G/∞ queue having arrival rate λ and mean service time M , the steady state probability distribution of the number N of customers in the system is well-known to be Poisson with mean λM , i.e.,

$$P(N = n) = \frac{(\lambda M)^n}{n!} e^{-\lambda M}, \quad n = 0, 1, 2, \dots$$

In this case, we can write the probability that there are N cars cruising for parking spaces is equal to

$$P(N = n) = \frac{\left(\frac{\lambda - S\mu}{\gamma}\right)^n}{n!} e^{-\frac{\lambda - S\mu}{\gamma}}, \quad n = 0, 1, 2, \dots$$

Here again we see that the mean number of cruising cars is equal to $\frac{\lambda - S\mu}{\gamma}$. But now we

know that the entire distribution – assuming our saturation conditions hold – is Poisson.

Finally, as saturation grows worse, that is as λ increases towards ever-greater congestion, the Poisson distribution becomes a Gaussian or Normal distribution.

The next step to take with this model is to place hourly prices on on-street parking and off-street parking. Then one makes certain model parameters dependent on these prices, especially the *price difference* between on-street and off-street parking. These ideas build on the suggestions of Shoup (Shoup D. C. 2005). As the price difference between on-street and off-street parking becomes less, one should have the rate γ at which one leaves the queue of cruising cars increase. That is, the desire to find an on-street parking space and

the patience it requires in the cruising queue will decrease as the price advantage of on-street parking decreases. Eventually as one gets closer to price parity, our approximate assumption of an endless queue of cruising cars becomes invalid and we must modify the model accordingly. Shoup's stated objective is to raise on-street prices so that one has roughly 15% of the on-street parking spaces available in steady state. For the model, this would require extending the state-rate-transition diagram down significantly into unsaturated states but still allowing the artifice of stopping at some left-most nonzero state that has very small steady state probability. We do not see the need to model the system all the way down to zero parking spaces being occupied.

Chapter 4. Congestion Pricing and Queueing Theory³⁴

Andreatta and Odoni (2003) showed how we can set congestion charge by following the economic principle: *The congestion cost caused by the entrance of a driver to a queueing system consists of the cost of delay to this driver (internal cost) plus the cost of additional delay to all other users caused by this driver (external cost)*. For example, if a driver enters into a congested road and experiences 5 minutes delay, the internal cost to him is the cost of 5 minutes. However, when the road is very congested, the entrance of this driver may delay each of 7 other drivers one additional minute. Then the external cost generated by him is the cost of 7 minutes to the other drivers. Economists argue that in order to achieve the most efficient use of the road facility, this external cost should be burdened by each driver. In economic terms, the external cost should be internalized. This was first pointed out by Vickrey (Vickrey W. 1969) and by Carlin and Park (Carlin A. and Park R. E. 1970): They claimed that, *“Optimal use of a transportation facility cannot be achieved unless each additional (marginal) user pays for all the additional costs that this user imposes on all other users and on the facility itself. A congestion toll not only contributes to maximizing*

³⁴ This discussion is based on Andreatta, G., and Odoni, A. R. (2003) *Analysis of Market-Based Demand Management Strategies for Airports and En Route Airspace*, in *Operations Research in Space and Air*, Ciriani, T. (ed.) Kluwer Academic Publishers, Boston; also Professors Odoni, A. R., and Larson, R. C. (2006) ‘Lecture Notes’ in *Logistical & Transportation Planning Methods*, MIT, Cambridge, MA.

social economic welfare, but is also necessary to reach such a result.” In 1954, Vickrey proposed an electronic Road Pricing (RP) system in detail to the Joint Committee on Washington Metropolitan Problems (Vickrey W. 1954). At the time, he also pointed out the importance of a variable pricing system for on-street parking spaces in order to ensure some vacancy to accommodate the demand and avoid unnecessary traffic congestion caused by on-street parking shortages.

We follow economic principles to obtain the “optimal” congestion pricing. Consider a queueing facility with a single type of user (driver) in steady state and let

λ = demand rate per unit of time by road users.

c = cost of delay per unit time per user.

C = total cost of delay per unit time incurred by all users in the system.

L_q = expected number of users in queue.

W_q = expected delay (cruising) time in queue for a random user.

We can also assume that $L=L_q$ and $W=W_q$, as in our parking model.

Then the time-average total delay cost per unit time can be written,

$$C = cL_q = c\lambda W_q,$$

where Little's Law is used. The *marginal delay cost* (MC) imposed by an additional road user can be obtained as,

$$MC = \frac{dC}{d\lambda} = cW_q + c\lambda \frac{dW_q}{d\lambda}.$$

The first term on the right is the internal cost experienced by the additional road user, and the second is the external cost due to the increase in the expected delay, $\frac{dW_q}{d\lambda}$, resulting from the increased traffic created by this user. Hence, we can write two components of the marginal delay cost MC as follows:

(1) Marginal internal cost: $MC_i = cW_q$

(2) Marginal external cost: $MC_e = c\lambda \frac{dW_q}{d\lambda}$.

Vickrey suggested that the marginal external cost MC_e should be imposed on each road user in order to realize socially “optimal” utilization of road resources. Hence, the congestion charge should be set equal to MC_e .

4.1. The Parking Pricing Model

Using the results in the previous chapter when the parking process in saturation, the total delay cost per unit time and associated marginal delay cost become

$$C = cL_q \approx (\lambda - S\mu) \frac{c}{\gamma}$$

and

$$MC = \frac{\partial C}{\partial \lambda} \approx \frac{c}{\gamma}.$$

We can also obtain the marginal internal cost and marginal external cost,

$$MC_i = cW_q \approx \left[1 - \left(\frac{S\mu}{\lambda} \right) \right] \frac{c}{\gamma}$$

$$MC_e = c\lambda \frac{\partial W_q}{\partial \lambda} \approx \frac{S\mu}{\lambda} \cdot \frac{c}{\gamma}.$$

The ratio MC_e/MC_i is

$$r = \frac{MC_e}{MC_i} \approx \frac{\frac{S\mu}{\lambda} \cdot \frac{c}{\gamma}}{\left(1 - \frac{S\mu}{\lambda} \right) \cdot \frac{c}{\gamma}} = \frac{\frac{S\mu}{\lambda}}{1 - \frac{S\mu}{\lambda}}$$

Here, we observe an interesting result. For a given c , the marginal delay cost to society is dependent only on γ and does not depend on $S\mu$ or λ . In a sense, in saturation each additional would-be parker “brings with him or her” an average of $1/\gamma$ of delay, to be

incurred by somebody or some combination of people. However, the marginal internal cost, the marginal external cost and their ratio r are dependent on $\frac{S\mu}{\lambda}$, which is the success probability for would-be parkers to find on-street parking spaces. The equation

$$MC_e \approx \frac{S\mu}{\lambda} \cdot \frac{c}{\gamma}$$

shows that the marginal external cost MC_e is proportional to the parking success probability. MC_e becomes larger when more would-be parkers expect they will find parking spaces. MC_e decreases if we reduce the number of on-street parking spaces S , or increase the arrival rate λ , or increase the renege rate γ . If half of would-be parkers will find a parking space, then marginal internal and external costs are equal. If 90% of all would-be parkers are denied parking, then the external cost MC_e associated with one new would-be parker is only $0.1c/\gamma$, whereas the internal cost MC_i is $0.9c/\gamma$. This is due to the fact that 90% of the time our new would-be parker arrives, he will be denied parking and will have to incur the mean cruising time (cost) $1/\gamma$ almost all by himself; he denies others only 10% of the time.

Because of the renege effect, the internal cost has a cap of c/γ , which prevents the congestion from becoming infinitely long. In fact, people usually change their behavior (renege in this case) after they are discouraged by observing the short supply (shortage in parking spaces in this case). This behavioral change that cruising drivers make while they

are in the system is often ignored in economics-based congestion pricing theory. However, this behavioral change plays a critical role in determining properties of the saturated (congested) system when supply is in shortage. Our result suggests that if short supply is expected, it is important to design a system that gives cruising drivers incentives to renege.

Following is the numerical example that illustrates the marginal internal and external costs at certain traffic level. We set $S\mu = 150$, $\gamma = 1$, and hypothetical demand function shown in the negative sloped dashed line in the following figure. Dashed dot line is the internal cost (MC_i) curve and solid line is the total delay cost (the sum of the internal cost (MC_i) and the external cost (MC_e)) curve. The traffic increases until the demand matches the internal cost. Hence, the traffic level realized would be $\lambda_{w/oCC}$. If congestion charge (CC) is set equal to MC_e , then the traffic level is decreased to $\lambda_{w/CC}$, which is the “optimal” traffic level where the demand and the total delay cost match.

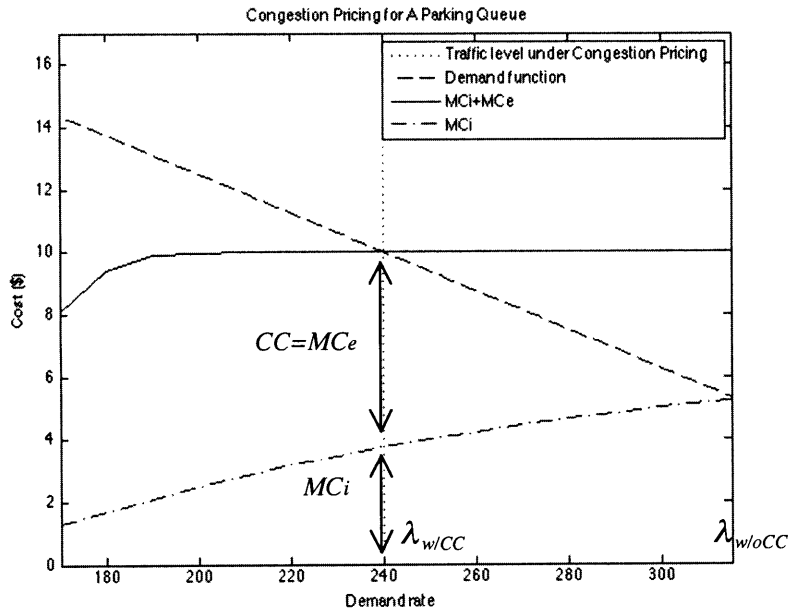


Figure 4-1 Congestion Pricing for a Parking Queue

4.2. Extending the Model to Include Heterogeneous Drivers

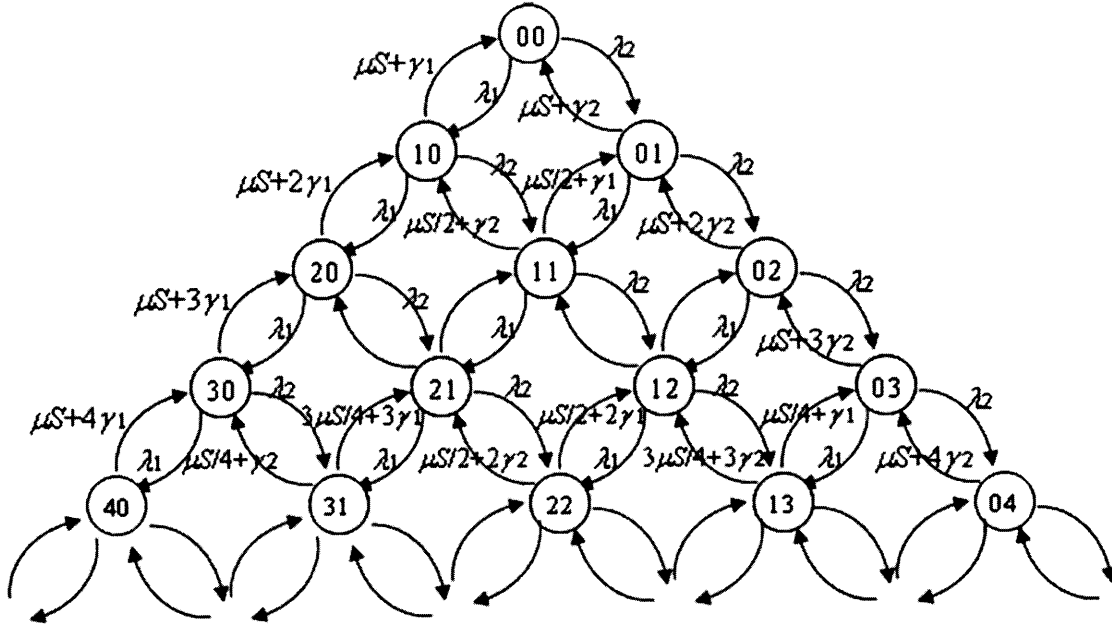
In this section, we confirm the intuition that “less affluent people are more likely to be successful on-street parkers than more affluent people”. Assume there are two types of drivers, or “would-be-parkers,” Type 1 and Type 2, whose corresponding arrival rates and reneging rates are λ_i and γ_i ($i=1, 2$), respectively. We construct a 2-dimensional state-rate-transition diagram for the Markovian queue created by two types of drivers. Assume that

each state is represented by the ordered pair n_1 and n_2 , which correspond to the respective numbers of Type 1 and Type 2 drivers in the system. The state-rate-transition diagram is shown in Figure 4-2.

As before, we continue to assume that $0 < P_{00} \approx 0$, but now for this 2-dimensional system.

Again as before, we assume that the road is congested, with either type of driver able to fill all available parking spaces: $\lambda_1 \geq S\mu$ and $\lambda_2 \geq S\mu$.

We can write a set of balance-of-flow equations, where the balanced flows occur across complete horizontal cuts of the network of Figure 4-2,



**Figure 4-2 State-Rate-Transition Diagram for
Queueing System with Two Types of Drivers**

$$(\lambda_1 + \lambda_2)P_{00} = (S\mu + \gamma_1)P_{10} + (S\mu + \gamma_2)P_{01} = S\mu(P_{10} + P_{01}) + \gamma_1(P_{10} + 0P_{01}) + \gamma_2(P_{01} + 0P_{10})$$

$$\begin{aligned} (\lambda_1 + \lambda_2)(P_{10} + P_{01}) &= (S\mu + 2\gamma_1)P_{20} + \left(\frac{1}{2}S\mu + \gamma_1\right)P_{11} + \left(\frac{1}{2}S\mu + \gamma_2\right)P_{11} + (S\mu + 2\gamma_2)P_{02} \\ &= S\mu(P_{20} + P_{11} + P_{02}) + \gamma_1(2P_{20} + P_{11} + 0P_{02}) + \gamma_2(2P_{02} + P_{11} + 0P_{20}) \end{aligned}$$

$$\begin{aligned} (\lambda_1 + \lambda_2)(P_{20} + P_{11} + P_{02}) &= (S\mu + 3\gamma_1)P_{30} + \left(\frac{2}{3}S\mu + 2\gamma_1\right)P_{21} + \left(\frac{1}{3}S\mu + \gamma_1\right)P_{12} \\ &\quad + \left(\frac{1}{3}S\mu + \gamma_2\right)P_{21} + \left(\frac{2}{3}S\mu + 2\gamma_2\right)P_{12} + (S\mu + 3\gamma_2)P_{03} \\ &= S\mu(P_{30} + P_{21} + P_{12} + P_{03}) + \gamma_1(3P_{30} + 2P_{21} + P_{12} + 0P_{03}) + \gamma_2(3P_{03} + 2P_{12} + P_{21} + 0P_{30}) \end{aligned}$$

...

$$(\lambda_1 + \lambda_2)(P_{(n-1)0} + P_{(n-2)1} + \dots + P_{0(n-1)}) = S\mu(P_{n0} + P_{(n-1)1} + \dots + P_{0n}) \\ + \gamma_1(nP_{n0} + (n-1)P_{(n-1)1} + \dots + 1P_{1(n-1)} + 0P_{0n}) + \gamma_2(nP_{0n} + (n-1)P_{1(n-1)} + \dots + 1P_{(n-1)1} + 0P_{n0})$$

...

Adding up the countably infinite set of balance equations, we obtain

$$(\lambda_1 + \lambda_2)\left(\sum_{n,m=0}^{\infty} P_{nm}\right) = S\mu\left(\sum_{n,m=0}^{\infty} P_{nm} - P_{00}\right) + \gamma_1\left(\sum_{n,m=0}^{\infty} nP_{nm}\right) + \gamma_2\left(\sum_{n,m=0}^{\infty} mP_{nm}\right).$$

Using the assumption $P_{00} \approx 0$, invoking the normalizing condition $\sum_{n,m=0}^{\infty} P_{nm} = 1$, and using the

definitions $L_1 = \sum_{n,m=0}^{\infty} nP_{nm}$ and $L_2 = \sum_{n,m=0}^{\infty} mP_{nm}$, we obtain

$$\lambda_1 + \lambda_2 = S\mu + \gamma_1 L_1 + \gamma_2 L_2.$$

We need to derive one more equation to solve for L_1 and L_2 . In order to do this, consider

the mean number of Type 1 and Type 2 renegers per hour, which are

$$\sum_{n,m=0}^{\infty} n\gamma_1 P_{nm} = \gamma_1 \left[\sum_{n,m=0}^{\infty} nP_{nm} \right] = \gamma_1 L_1 \text{ and } \gamma_2 L_2, \text{ respectively. Using these, the steady state mean}$$

number of parking spaces available and taken by Type 1 and Type 2 parkers per hour are

$\lambda_1 - \gamma_1 L_1$ and $\lambda_2 - \gamma_2 L_2$, respectively. Note that the sum of the mean number of parking

spaces available and taken by Type 1 and Type 2 parkers per hour is

$(\lambda_1 - \gamma_1 L_1) + (\lambda_2 - \gamma_2 L_2) = S\mu$, using the equation $\lambda_1 + \lambda_2 = S\mu + \gamma_1 L_1 + \gamma_2 L_2$. Note also that both $\lambda_1 - \gamma_1 L_1$ and $\lambda_2 - \gamma_2 L_2$ are positive because the mean number of reneges $\gamma_1 L_1$ and $\gamma_2 L_2$ must be less than the arrival rate λ_1 and λ_2 , respectively, in steady state.

We now argue that the proportion of parking spaces taken hourly by Type 1 (Type 2) drivers is equal to the proportion of cruising drivers who are Type 1 (Type 2). For if not, then Type 1 (Type 2) drivers would be more or less skilled than Type 2 (Type 1) drivers at finding parking spaces. Due to the SIRO queue discipline that rewards that driver, Type 1 or Type 2, who just happens to be closest to the newly available parking space, each type of driver is by definition equally skilled. And clearly the proportion of parking spaces taken per hour by Type 1 (Type 2) drivers is equal to the fraction of parking spaces occupied by Type 1 (Type 2) drivers. For if not, then the parking time statistics of the two types of drivers would differ, and this is not allowed in our model.

Invoking these results, we can write

$$\frac{\lambda_1 - \gamma_1 L_1}{L_1} = \frac{\lambda_2 - \gamma_2 L_2}{L_2}, \text{ or, simplifying, } \gamma_2 - \gamma_1 = \frac{\lambda_2}{L_2} - \frac{\lambda_1}{L_1}$$

Using the equation $\lambda_1 + \lambda_2 = S\mu + \gamma_1 L_1 + \gamma_2 L_2$, we have

$$\gamma_2 - \gamma_1 = \frac{\lambda_2}{L_2} - \frac{\lambda_1}{\frac{\lambda_1 + \lambda_2 - S\mu}{\gamma_1} - \frac{\gamma_2 L_2}{\gamma_1}}$$

and

$$\gamma_2 - \gamma_1 = \frac{\lambda_2}{\frac{\lambda_1 + \lambda_2 - S\mu}{\gamma_2} - \frac{\gamma_1 L_1}{\gamma_2}} - \frac{\lambda_1}{L_1}.$$

Since both $\lambda_1 - \gamma_1 L_1$ and $\lambda_2 - \gamma_2 L_2$ are positive, the denominators in the equations above are all positive. Therefore, unique positive solutions for both L_1 and L_2 are guaranteed in the above equations. Analytical solutions can be obtained for both L_1 and L_2 using the quadratic formula.

The method extends to three or any number of different types of drivers: if there are n types of drivers in the system, we can obtain the proportion of each (L_1, L_2, \dots, L_n) in the system by solving n equations

$$\lambda_1 + \lambda_2 + \dots + \lambda_n = S\mu + \gamma_1 L_1 + \gamma_2 L_2 + \dots + \gamma_n L_n$$

and

$$\frac{\lambda_1 - \gamma_1 L_1}{L_1} = \frac{\lambda_2 - \gamma_2 L_2}{L_2} = \dots = \frac{\lambda_n - \gamma_n L_n}{L_n}.$$

For simple illustrative purposes, consider a numerical example. Assume there are two types of drivers: 200 less affluent people per hour arrive to the system and their per-person reneging rate is 1/hr., and 200 affluent people per hour arrive to the same system and their per-person reneging rate is 3/hr. Both types of drivers are trying to find on-street parking spaces which capacity is $S\mu = 50$ /hr. In this case, one could argue that less affluent people value their time at a rate of 1/3 that of affluent people. By placing numbers in the equations above, we obtain

$$3 - 1 = \frac{200}{L_2} - \frac{200}{\frac{200 + 200 - 50}{1} - \frac{3}{1}L_2} \quad \text{and} \quad 3 - 1 = \frac{200}{\frac{200 + 200 - 50}{3} - \frac{1}{3}L_1} - \frac{200}{L_1}.$$

Solving, we have $L_1 = 164$ and $L_2 = 62$. Hence, the ratio of less affluent and affluent in parking spaces are

$$\text{Less Affluent : Affluent} = L_1 : L_2 = 164 : 62 = 73\% : 27\%.$$

The interpretation is as follows: Even though the less affluents' arrival is half of the total arrival rate, less affluent people occupy nearly three quarters of the on-street parking spaces because of their lower reneging rate, their greater "patience" while cruising for an available parking space. Furthermore, the success rate of finding available parking spaces for less affluent and affluent are

$$\frac{\lambda_1 - \gamma_1 L_1}{\lambda_1} = \frac{200 - 1 \cdot 164}{200} = 18\% \text{ and } \frac{\lambda_2 - \gamma_2 L_2}{\lambda_2} = \frac{200 - 3 \cdot 62}{200} = 7\%, \text{ respectively. Therefore,}$$

in terms of distributional equity, the provision of on-street parking spaces can be seen as “good” because less affluent people tend to utilize inexpensive parking more often than affluent people. However, the result also suggests that less affluent people are more apt to cruise than affluent people, thereby maintaining levels of street congestion that may be found unacceptable. The way to fix that problem is to raise the price of on-street parking, and that would increase the reneging rate of both less affluent and affluent people since the price advantage of cruising for on-street parking diminishes.

Finally, we conclude this section with an extension to congestion pricing for heterogeneous drivers. Assume there are multiple types of drivers, with drivers of type k having arrival rate λ_k , reneging rate γ_k , expected number of cruising drivers L_k , expected cruising time W_k , delay cost for type k driver c_k , and marginal delay cost imposed by an addition of type k driver $MC(k)$. In addition to equations

$$\sum_m \lambda_m = \mu S + \sum_m \gamma_m L_m \text{ and } \frac{\lambda_1 - \gamma_1 L_1}{L_1} = \frac{\lambda_2 - \gamma_2 L_2}{L_2} = \dots = \frac{\lambda_n - \gamma_n L_n}{L_n}$$

which we already derived, we have an equation for marginal delay cost for type k drivers

$$MC(k) = \frac{dC}{d\lambda_k} = c_k W_k + \sum_m c_m \lambda_m \frac{dW_m}{d\lambda_k}.$$

This is a simple extension of marginal delay cost for homogeneous drivers

$$MC = \frac{dC}{d\lambda} = cW_q + c\lambda \frac{dW_q}{d\lambda}.$$

As before,

(1) Marginal internal cost for type k driver: $MC_i(k) = c_k W_k$

(2) Marginal external cost for type k driver: $MC_e(k) = \sum_m c_m \lambda_m \frac{dW_m}{d\lambda_k}.$

The second term $MC_e(k) = \sum_m c_m \lambda_m \frac{dW_m}{d\lambda_k}$ corresponds to the congestion charge for type k

drivers, which can be calculated computationally. Note that an appropriate level of

congestion charge is different among different types of drivers.

Chapter 5. Evaluation of Cruising Traffic

Despite that parking pricing has many practical benefits as we have seen in chapter two, on-street parking spaces in many locations have still remained unmanaged without being recognized as a potential cause of congestion. Part of the reason is that vehicles cruising for a spot are not clearly visible by observation. In this chapter, we introduce a simple method to evaluate the level of parking-induced cruising quantitatively. For example, using the “Parking Queue” model we developed in chapter 3 and collected data, we can estimate the probability that a driver can find a vacant on-street parking spot and the number of cruising vehicles, which are obtained by simple observation of driving behaviors without the necessity of conducting a large intercept survey of visitors.

5.1. Some Performance Measures for Parking-Induced Traffic

Many quantities can be derived analytically using the results from chapters 3 and 4. In this section, we introduce several important indices that could be used for evaluating a performance of parking facilities. We continue to assume that the parking system is almost always saturated ($\lambda > S\mu$) and apply “Parking Queue” model. The following is the summary of several important performance indices:

Table 5-1 Performance Indices when Parking System is Saturated

Performance index	Analytical Expression
Expected number of cruising vehicles per on-street parking space	$\frac{L_q}{S} = \frac{\lambda - S\mu}{S\gamma} = \frac{\mu W_q}{1 - \gamma W_q}$
Expected cruising time	$W_q = \frac{L_q}{\lambda} = \frac{\lambda - S\mu}{\gamma\lambda}$
Probability that a random arrival obtains a parking space	$\frac{S\mu}{\lambda} = \frac{S\mu W_q}{L_q} = 1 - \gamma W_q < 1$
Congestion Charge	$MC_e = \frac{S\mu}{\lambda} \frac{c}{\gamma} = (1 - \gamma W_q) \frac{c}{\gamma}$

As derived in chapter 3, the expected number of cruising vehicles is

$$L_q = \frac{\lambda - S\mu}{\gamma}.$$

Using Little's Law, we can obtain the expected cruising time as

$$W_q = \frac{L_q}{\lambda} = \frac{\lambda - S\mu}{\gamma\lambda}.$$

The expected number of cruising vehicles per on-street parking space is a convenient

performance index. Using the result $L_q = \frac{\lambda - S\mu}{\gamma}$ and W_q , this index becomes

$$\frac{L_q}{S} = \frac{\lambda - S\mu}{S\gamma} = \frac{\mu W_q}{1 - \gamma W_q}.$$

Note that we can evaluate this index without knowing the number of arrivals λ .

Alternatively, we can modify $\frac{L_q}{S}$ as $\frac{L_q}{S} = \frac{\lambda - S\mu}{S\gamma} = \frac{\mu}{\gamma} \left(\frac{\lambda}{S\mu} - 1 \right)$. This representation shows that the expected number of cruising vehicles per space (or excess demand for on-street parking space) is linear to the normalized arrival rate $\frac{\lambda}{S\mu}$ with a coefficient $\frac{\mu}{\gamma}$. For example, if the normalized arrival rate $\frac{\lambda}{S\mu}$ decreases while $\frac{\mu}{\gamma}$ remains constant, then the number of cruising vehicles is expected to decrease linearly. This is different from nonlinear behavior of the queue in general.

Cruising rate is one of the most important indicators which Shoup originally used in his book and papers in order to illustrate the seriousness of parking-induced congestion.

Cruising rate can be obtained from observation using the index $\frac{L_q}{S}$. Suppose you observe the total number of vehicles (on average) $L_{q,total}^{observed}$ and the total number of on-street parking spaces $S^{observed}$ along the street you are interested in. Then the cruising rate becomes

$$\frac{L_{q,total}^{observed} - \frac{L_q}{S} S^{observed}}{L_{q,total}^{observed}}.$$

For example, if L_q/S is 20% and we observe 10 vehicles along the street with 20 on-street parking spaces, we estimate that 4 vehicles (20% of 20 spaces) are cruising, and therefore,

cruising rate is 40% (4 cruising vehicles out of 10 total vehicles) in this case. In practice, cruising rate can not be a good performance index since it varies hugely street by street depending on how much through traffic is passing through a certain street. Another problem is that there usually exist live double parkers waiting for a spot when parking spaces are in high demand.

The rate of successful parking $\frac{S\mu}{\lambda}$ can also be obtained using W_q and the Little's Law:

$$P\{\text{a random arrival obtains a parking space}\} = \frac{S\mu}{\lambda} = \frac{S\mu W_q}{L_q} = 1 - \gamma W_q < 1.$$

The above relation suggests that if $S\mu/\lambda$ stays the same, γ and W_q are inversely proportional to each other.

Finally, congestion charge can be obtained by calculating a marginal external cost.

$$MC_e = c\lambda \frac{\partial W_q}{\partial \lambda} \approx \frac{S\mu c}{\lambda \gamma} = (1 - \gamma W_q) \frac{c}{\gamma},$$

where c is the cost of delay per unit time per driver.

5.2. Outline of Survey

Locations of data collection

We conducted interviews on Saturday noon at Newbury Street and at Boston Common, where on-street parking demand is huge. The details of these locations are as follows:

(A) Location1: Newbury Street

Many on-street parking spaces are distributed along Newbury Street. Some of the off-street parking options are 200 Newbury Street Garage (\$5 for ½ hour (max \$25)) and Prudential Center Garage (\$9 for 1 hour, \$26 for 2 hours (max \$39 daily) or \$12 for 4 hours, \$20 for 5 hours after \$10 purchase at Prudential Center).

(B) Location2: Boston Common

On-street parking spaces are distributed around Boston Common. Double parking is often observed in this area. Off-street parking option is Boston Common Garage (\$8 for 1 hour, \$12 for 2 hours, \$16 for 3 hours (max \$27 daily)).

Questions asked during interviews

We asked questions of those who had just entered a vacant on-street parking spot during most congested peak hours. Questions asked were as follows:

- (1) Cruising time: How long did you spend searching for a vacant on-street parking spot
this time?
- (2) Reneging time: How long is the maximum time you can spend on searching for a
vacant spot before giving up and seeking garage parking?
- (3) Reneging destination: What would you do if you could not find any vacancy this time?
Do you go to garage, or to another area?
- (4) Parking time: How long do you plan to park in this spot today?
- (5) Minimum price differential for immediate reneging: How much extra cash would you
pay if you were guaranteed to park here immediately?
- (6) Demand flexibility: Would you have come here by car today if there were no on-street
parking?
- (7) Purpose of visit: What is the general purpose of the visit here today?
- (8) Heterogeneity of drivers: Check the make/type of cars (by observation)
- (9) Cruising ratio is observed whenever possible

5.3. Results and Data Analysis

Mean parking time $1/\mu$

Although parking time limit for on-street parking is two hours for both locations, the result of the survey shows that the averages are 120 minutes at Newbury Street and 158 minutes³⁵ at Boston Common, from which we obtain $\mu = 0.5$ /hour and 0.38 /hour for Newbury Street and Boston Common, respectively.

Mean cruising time W_q

The cruising time distribution for successful parkers follows a negative exponential distribution. The mean cruising time for successful parkers W_q is obtained by fitting negative exponential curve by least squares. We obtained $1/W_q = 9.8$ /hour and 6.7 /hour for Newbury Street and Boston Common, respectively. We used STATA for statistical analysis. R^2 is 0.9650, adjusted R^2 is 0.9563 for Newbury Street data and R^2 is 0.9697 and adjusted R^2 is 0.9621 for Boston Common data.

³⁵ Drivers keep adding quarters to extend parking time.

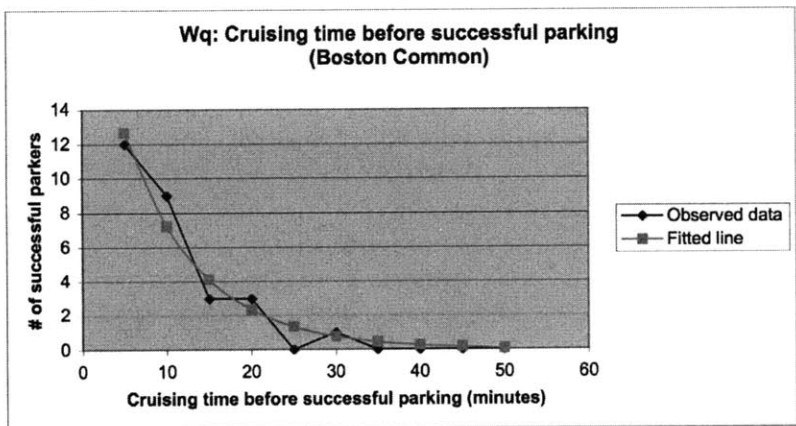
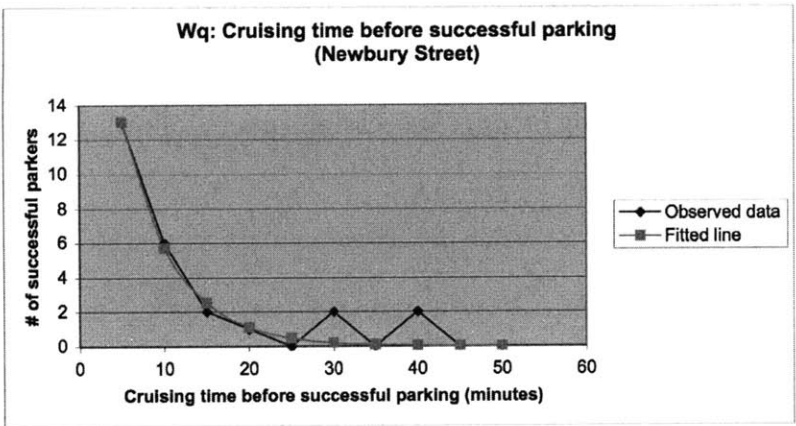


Figure 5-1 Cruising Time Distributions for Successful Parkers

We observed some discrepancies from negative exponential distributions above. These irregularities may be an indication of heterogeneity of drivers' type (i.e., existence of drivers whose reneging processes are different from Poisson). However, the current size of data is too small to confirm the "heterogeneity" of drivers.

Poisson renegeing rate γ

The distribution of the stated maximum cruising time for successful parkers follows an atypical distribution.

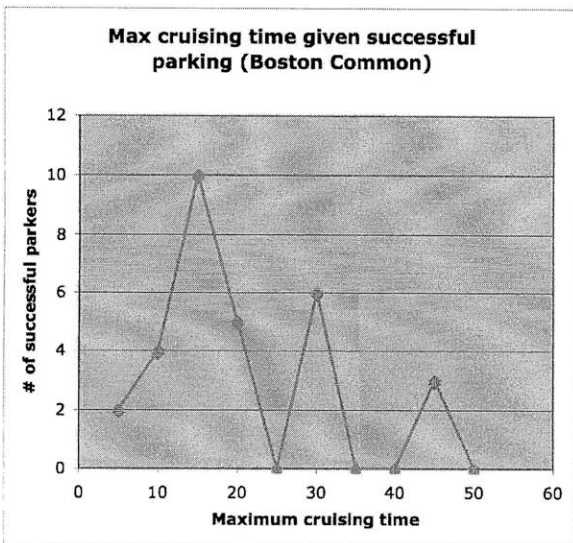
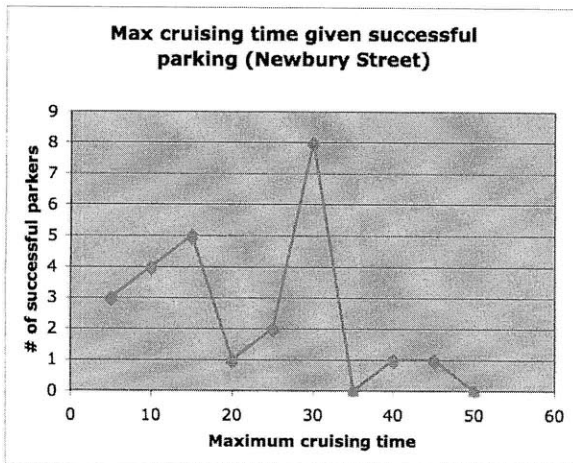


Figure 5-2 Stated Maximum Cruising Time Distributions for Successful Parkers

By subtracting their actual cruising time from their stated maximum cruising time, we can estimate extra cruising time drivers would like to spend for cruising. The results are as follows:

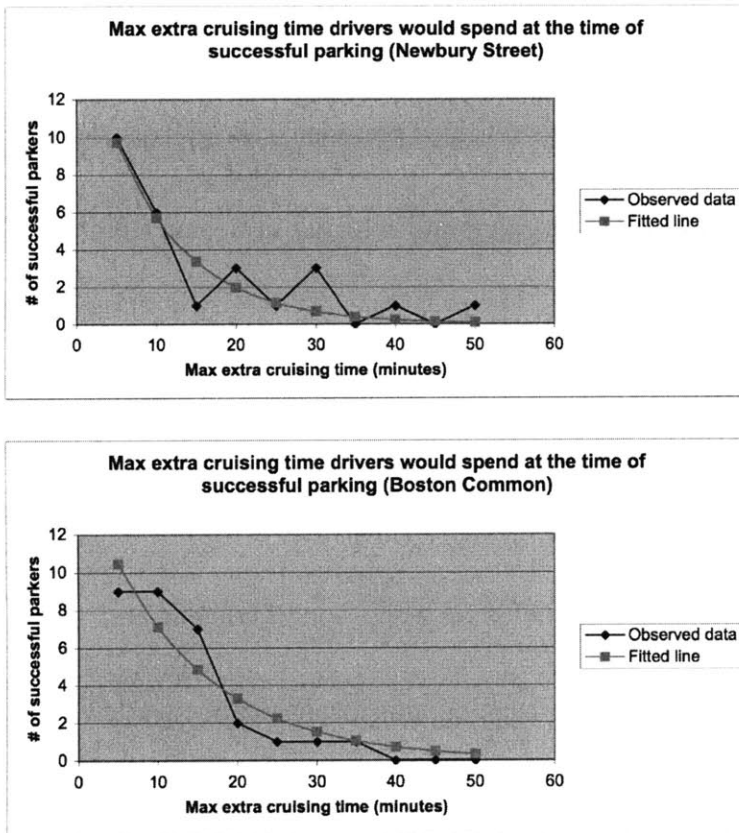


Figure 5-3 Reneging Time Distributions for Successful Parkers

We found this reneging time roughly follows a negative exponential distribution. Poisson reneging rate γ is obtained by fitting negative exponential curve by least squares. Again using STATA, we obtained $\gamma = 6.4$ /hour and 4.6 /hour for Newbury Street and Boston

Common, respectively. R^2 is 0.9128, adjusted R^2 is 0.8910 for Newbury Street data and R^2 is 0.9327 and adjusted R^2 is 0.9159 for Boston Common data. R^2 values are less than those of observed cruising time (which means the estimation is less precise). One of the reasons is that the reneging time is their stated preference (SP) and may be affected by how we asked questions, whereas observed cruising time is revealed preference (RP) which does not have such a problem and is more precise. Reneging rate is higher in Boston Common because garage parking is less expensive than at Newbury Street.

The above graphs suggest that drivers' decision to cruise is independent from the time they already spent for cruising (i.e., Markov Property holds for a decision of cruising and reneging process is memoryless.) Economically speaking, this means that the wasted cruising time is a "sunk cost" for them, and a "sunk cost" does not affect the future cruising decisions.

Other observations

Cruising ratio in Boston Common (less than 10%) was less than the ratio in Newbury Street (30-50%) due to a large through traffic.

There were many double parking vehicles observed in Boston Common area. The results obtained at Boston Common may be affected by these double parkers.

5.4. Cruising Traffic and Congestion Charge in Boston

Using estimated parameters above, we found that success rate of finding an on-street parking space is higher in Newbury Street (35%) compared to Boston Common (31%).

The number of cruising vehicles per space, L_q/S , is higher in Boston Common (18%) than Newbury Street (14%), but similar.

Assuming the cost of time in dollar is \$20 /hour, the congestion charge should be about \$1 /hour for the cruising drivers. Note that this congestion charge only considers the cost for cruising drivers. If we take seriously into account environmental and health concerns when evaluating the cost of congestion, the overall marginal external cost becomes large. The appropriate level of congestion charge is difficult to determine because people have different perspectives on what should be included in the system.

Chapter 6. Policy Measures to Reduce Cruising Vehicles

We already discussed how to reduce cruising traffic by imposing congestion charge on drivers. However, congestion charge is just one of many parking policies. In this chapter, we discuss the guiding principles of parking policies. Analytical forms of performance measures help us understand the principles.

Why is cruising traffic $L_q = \frac{\lambda - S\mu}{\gamma}$ so heavy? The reasons are low departure rate, low renegeing rate, and high arrival rate. In the following, we discuss possible measures to solve these three problems with examples.

6.1. Increasing Departure Rate

To increase departure rate μ , we can simply increase parking price. More efficient way is to punish longer-time on-street parkers and prioritize shorter-time parkers. This can be achieved by progressive pricing scheme. For example, progressive on-street parking pricing is implemented in Manhattan: fees are \$2 for the first hour, \$3 for the second hour, and \$4 for the third hour.

The reduction of parking time limits also increases departure rate μ and reduces parking queue. We can dynamically change parking time limits or set peak-time/off-peak-time parking time limits. Any time limit measures should be accompanied by strict enforcement in order to prevent drivers from parking longer than time limit by adding extra coins. Setting signboard indicating penalty fees explicitly would also discourage overtime parkers who do not realize the cost of parking violation.

6.2. Increasing Reneging Rate

Reneging rate plays important role in cruising traffic since reneging rate is in the denominator. To increase reneging rate, off-street parking pricing structure should be fair and attractive to shorter-time parkers. However, we often observe the opposite parking pricing policy in a city. Examples of undesirable, aggressive fee structures of garage parking can be seen in many cities: for example, parking fee quickly reaches its daily maximum after two or three hours of parking if we use private parking garages. This fee structure especially punishes shorter-time parkers and gives a disincentive for cruising drivers to “renege” to garage parking. Proportional pricing structures (up to at least 4-5 hours) can make two-hour parkers feel that a parking fee is fairer to them.

In Japan, in contrast to U.S., unmanned parking lots with proportional parking fee structure is very popular.³⁶ They are usually called “100yen (about \$1) coin parking.”³⁷ Their minimum fee increment varies from 100yen /6 minutes to 100yen /60 minutes. This proportional fee parking is one of the most successful parking business models in Japan. Their business is still growing rapidly backed up by (one can hypothesize) drivers’ strong demand for fair pricing.

Furthermore, a free first thirty-minute parking scheme is implemented in about 30 public parking lots in Tokyo.³⁸ The purpose is to encourage the use of garage parking rather than illegal on-street parking.³⁹ Garage parking capacity is not be affected heavily by this policy because each free parking time is short. Hence, this free parking policy is socially desirable, although some subsidy may be required for private garage parking owners.

Parking information system can also increase reneing rate, and is one of the least expensive measures that we can take. According to our survey, many drivers are optimistic

³⁶ For example, see <http://times-info.net/map/> (in Japanese) (accessed July 31, 2009)

³⁷ They accept bills and credit cards in addition to coins.

³⁸ <http://www.tmpc.or.jp/contents/parking/30.html> (in Japanese) (accessed July 31, 2009)

³⁹ On-street parking is not allowed at most places in Japan.

about finding an on-street parking spot.⁴⁰ We also observed many cruising drivers who did not know the location/price/availability information about parking garages nearby.⁴¹ Off-street parking information would change decisions to use cars for those who do not wish to try their luck.

6.3. Reducing Arrival Rate

People would not drive into downtown and cruise around if they had alternative options.

Provision of alternatives contributes to reduction in arrival rate and hence, to the reduction of cruising queue length. Extensive public transit or convenient park and ride system are important in this regard.

Imposition of congestion charge MC_e on drivers through road pricing or parking pricing is also very effective to reduce arrival rate. In reality, parking price increase would impact on all three parameters λ , μ , and γ , so the appropriate level of the charge would be determined by a trial-and-error approach.

⁴⁰ According to our survey, about half of the drivers said that they would not use cars if on-street parking is not available. However, our estimate of success rate of finding a spot is only one third. This shows that drivers are optimistic about finding a spot.

⁴¹ We found that almost no (or very limited) off-street parking information is provided to drivers in Newbury Street.

Congestion charge does not have to be a monetary charge. High cost of cruising is equivalent to congestion charge for drivers. This can be achieved by banning double parking and eliminating efficient cruising paths.

Chapter 7. Recommended Further Research

Each measure reduces the size of parking queue in a different manner. The following table summarizes policy tools and their impact on parameters. From the table, we should know that increasing parking fees – never a popular parking policy – is not the sole option to reduce parking queue. For example, if accompanied by milder measures such as altering the priorities of shorter-time (e.g., 15 minutes or 1 hour) and longer-time (e.g., 2 hours or more) parkers, parking fee increases could be minimized. Since these measures are implemented together in many cases, it is important to consider further how these policy measures should be combined in order to affect all three parameters in a favorable direction to make the overall parking policy socially efficient, economical, and politically palatable.

Table 7-1 Parking Policy Tools and Parameters

	Measures	$\mu \uparrow$	$\lambda \downarrow$	$\gamma \uparrow$
(I) Internalization of a negative externality	(a) Pricing schemes (high parking price, progressive pricing, dynamic pricing)	○	○	○
	(b) Increasing the cost of cruising (banning double parking, imposition of high cost for cruising behavior)		○	○
(II) Reduction of a negative externality	(c) Parking time limit (strict enforcement, high/progressive penalty, dynamic parking time limit, priority parking spaces for shorter-time parkers)	○		
	(d) Provision of alternatives: park and ride system ^A , extensive public transportation system ^B , fair pricing for garage parking ^C		○ A B	○ C
	(e) Parking information (congestion level, waiting (cruising) time, parking fine, parking location/price/availability)		○	○

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