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Authors
Anas, Alex
Lindsey, Robin

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Reducing Urban Road Transportation Externalities: Road Pricing in Theory and in Practice

Alex Anas* and Robin Lindsey†

Introduction

Urban road transportation causes several major negative externalities. First, the costs of greenhouse gas emissions from motorized private and public vehicles are borne globally. Second, other air pollutants and noise from urban road transportation affect road users and others locally. Third, while the costs of congestion (time delays and extra fuel consumption), accidents, and infrastructure damage are largely borne by motorists collectively, there is still an externality because individual motorists increase these costs for other motorists. Because of these externalities, motorists do not bear the full social marginal costs of driving and they drive too much.

Urban road transportation causes several other externalities as well, including water pollution, vibrations, and visual intrusion. Roads also create a barrier to bicyclists and pedestrians. Moreover, when parking is underpriced, the time spent searching for parking, excessive use of land for parking, the contribution to the urban heat island effect, and problems of drainage can be significant in urban areas (Shoup 2005). In addition, fuel consumption can impose costs at the national level due to monopsony power in the world oil market and energy insecurity, although by most estimates the average costs are small (Bickel et al. 2006; Delucchi and McCubbin 2009).

Many policy instruments can be used to control road transportation externalities, but all have their limitations. In the United States, vehicle emissions standards and ceilings on regional air quality have helped reduce emissions per vehicle kilometer. Regulating vehicle safety, building

*Department of Economics, State University of New York at Buffalo, 415 Fronczak Hall, North Campus, Amherst, NY 14260, USA. Telephone: 716-645-8663; Fax: 801-749-7805; e-mail: alexanas@buffalo.edu.
†Sauder School of Business, University of British Columbia, 2053 Main Mall, Vancouver, British Columbia, Canada V6T 1Z2. Telephone: 604-822-3323; Fax: 604-822-4977; e-mail: robin.lindsey@sauder.ubc.ca.

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safer roads, stricter enforcement of traffic rules, and experience rating of insurance premiums have all helped reduce accident rates per kilometer driven. But building safer cars can induce faster and less careful driving, and regulations mandating greater vehicle fuel efficiency can cause a rebound effect when a reduction in the monetary cost of driving per kilometer induces more driving.

The cost of driving depends on distance driven, road and vehicle characteristics, regulations, and level of congestion. Vehicle sales taxes and registration and licensing fees entail fixed charges that do not vary with distance driven. Fuel taxes offer a first-best instrument for internalizing the costs of CO_2 and other greenhouse gas emissions, as well as air pollution costs that are proportional to fuel consumption. However, fuel-related externalities generally account for a small fraction of the total external societal costs of driving. Tsekeris and Voß (2008), Parry (2009), estimate that for light-duty vehicles in the United States, fuel-related externalities are eighteen cents per gallon, compared to time-delay and other distance-related costs of $2.10 per gallon (converted using average vehicle fuel economy). In addition, the costs of congestion and accidents vary widely, whereas fuel use is relatively insensitive to time of day, type of road, and traffic volume. Fuel taxes per kilometer of driving decrease with vehicle fuel economy, but the time-delay costs of congestion are little related to fuel economy. Moreover, high fuel taxes induce switching to fuel-efficient, electric, and alternative fuel vehicles and therefore become less effective at reducing travel over time. In many developing countries with rapidly rising incomes, values of time are rising and the time-delay externality of congestion is increasing more quickly than other costs.

The problem of traffic congestion has been addressed by building new roads; improving public transportation, traffic control, and other travel demand management policies; adoption of advanced traveler information systems;[1] and land-use planning. But these measures can make driving cheaper and more pleasant, which encourages additional driving. While these policies may reduce the level of congestion, and thus the gap between marginal social and average private costs, excess congestion still remains.

According to the theory of welfare economics and externalities pioneered by Pigou (1920), a tax or toll is needed to correct the externalities of urban road transportation. Road pricing has two advantages over command-and-control policies such as bans on driving and restrictions on the days when a vehicle can be driven (based on license plate numbers). First, it induces adjustments in trip frequencies, destination, mode, and time of day and route, as well as in long-run location decisions. Second, road pricing can be varied with the magnitude of the congestion externality according to place, time of day, and type of vehicle.

Most previous studies of urban road pricing have focused on its role in relieving congestion. Only recently has attention turned toward using road pricing as an instrument to improve air quality. This article, which is part of a symposium on Transportation and the Environment, examines the environmental as well as the congestion relief benefits of road pricing in theory and in practice.[2] Our discussion does not include the specialized topics of

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[1] Advanced traveler information systems refers to a broad array of sources that provide information about travel conditions, such as Internet websites, 511 phone systems in the United States, cell phones, and other handheld devices.

[2] The other two articles in this symposium are Proost and Van Dender (2011), who examine projections of the future demand for road transport and assess long-term policy issues and options, and Anderson et al. (2011), who examine the impacts and efficiency of automobile fuel economy regulations in the United States and other countries.

revenue generation, pricing of parking congestion, private toll roads, pay-as-you-drive car insurance, and truck tolls. Rather, we address four broad issues related to urban road pricing.

First, real-world pricing schemes are imperfect and there is no guarantee that their benefits will exceed their setup and operating costs (Eliasson 2009). Thus, it is important to identify the effects of existing schemes and assess whether their benefits exceed their costs. Second, road pricing can yield environmental benefits that the public supports. According to Oberholzer-Gee and Weck-Hannemann (2002), for example, people are generally more interested in cleaner air than in congestion relief. This raises the second issue, which is how the potential environmental benefits from road pricing compare to the congestion relief benefits. Third, as Thomson (1977) noted, public transport provides a sort of "safety valve" for traffic congestion. To date, all urban road congestion pricing schemes have been implemented in cities with good public transport (e.g., Singapore, London, Stockholm). Thus, it is important to examine how the availability of good urban public transport affects the impact and acceptance of road pricing policies. Finally, there have been conflicting views on the viability of road pricing (e.g., see Borins 1988 versus Richards 2008). This leads to the fourth issue we address, which is to identify the conditions under which urban road pricing is likely to be both economically attractive and politically feasible and to determine whether such policies are likely to become widespread in the foreseeable future.

Our review is organized as follows. The next section discusses road pricing theory and policy options. This is followed by a review of experience with urban road pricing schemes in Singapore, London, Stockholm, and Milan. The next section discusses the distributional impacts and public acceptance of road pricing. The final section summarizes the main findings of the review and offers some thoughts about the future of urban road pricing.

Road Pricing Theory and Policy Options[3]

This section discusses the theory of congestion pricing of roads. It begins with the simple case of tolling congestion on a single road and then describes some of the complications that make road pricing schemes challenging to design in practice.

Pricing Congestion

Congestion is the most costly urban road transportation externality (Small and Verhoef 2007), and congestion relief has been the main target of urban road pricing policy. Congestion pricing calls for a toll to confront motorists with the cost of the congestion delays they impose on other drivers. For a single road link in isolation, the first-best toll is an increasing function of the level of traffic on the link.[4] If each link is efficiently priced, it is unnecessary to consider how the toll on one link affects flows on other links (Yang and Huang 1998).[5] Thus, only

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[3] For more comprehensive reviews of the theory, see Small and Verhoef (2007), Tsekeris and Voß (2008), Parry (2009), and Anas (2010).

[4] The first-best toll is $\tau = c'(Q)Q$, where Q is traffic flow, $c(Q)$ is the generalized cost of a trip (value of time-delay plus monetary cost), and $c'(Q) > 0$ is its derivative (Small and Verhoef 2007).

[5] This is because the net benefit of small changes in other flows is zero when they are efficiently priced. For the same reason, it is also unnecessary to take into account how optimal tolls on other links are affected.

link-specific information is required to set the toll and not the paths that vehicles follow through the road network. However, link-specific tolls are hard to calculate precisely for several reasons. First, the generalized cost of a trip varies with fuel consumption and the values of time for the driver and passengers. Second, to calculate the toll, the values of time of the other drivers and passengers using the same link must be known. Third, congestion depends on lane width, travel speed, and the mix of light and heavy vehicles on the road, which requires normalization to passenger car equivalents. Fourth, congestion varies by time of day, as well as by week and season. This means that congestion tolls should also vary over time. Fifth, in principle, tolls should be adjusted for accidents, bad weather, and other shocks. The amount of information and computer power required to set tolls as a function of all these factors is likely to be very costly.

Pricing Accident Externalities

Accidents are the second largest road transportation externality and result in personal injuries, fatalities, and damage to vehicles and other property. Expected accident costs depend on traffic volumes and speeds, the mix of vehicle types, the presence of pedestrians and bicyclists, road design, pavement conditions, and weather. The elasticity of expected accident costs per vehicle kilometer with respect to travel volume can be negative if a driver slows down traffic enough, so that the higher probability of accidents from more traffic is outweighed by the lower damage if an accident occurs. The relationship between accident risk, speed, and traffic density depends on the trade off that drivers make between travel time and risk and on their safety effort. According to Hensher (2006) and Steimetz (2008), the combined cost of the accident risk and driver effort devoted to safe driving per car kilometer is similar in magnitude to the time-delay cost of congestion. These costs are external to the driver and thus call for tolls above the level based on congestion externalities alone.

Pricing Emissions

Vehicle emissions depend on fuel type, engine displacement, maintenance, engine temperature, and the driving cycle or time profile of speed. For each pollutant, emissions per kilometer are a flat-bottomed, U-shaped function of speed with a minimum at an intermediate speed that depends on the pollutant. In heavy congestion, speeds are generally well below the minimum.

The costs of emissions rise with greater pollution exposure in densely populated areas. As Johansson (1997) and Johansson-Stenman (2006) point out, emissions also impact nearby road users. When congestion increases, speed decreases and vehicle density and exposure increase; the optimal emissions charge should reflect this higher exposure (Johansson-Stenman 2006).

Pricing Only Some Roads or Road Links

Under cordon schemes, vehicles can be charged for crossing cordons in the inbound direction, the outbound direction, or both. Several Norwegian cities have single cordons, but these cordons are designed to generate revenue rather than manage traffic. Stockholm's congestion charge has a single cordon, and Singapore's Electronic Road Pricing (ERP) scheme includes three restricted zones around the central business district, which effectively operate as small cordons. Cordons have an advantage of operational simplicity. Schemes with large and/or multiple cordons can charge large numbers of vehicles without creating undue traffic diversion. However, cordon schemes are relatively crude since payments are made in discrete lumps and motorists not crossing any cordon pay nothing. Optimizing the number and locations of cordons can be computationally difficult, and the estimated benefits can be sensitive to the design (May et al. 2008).

Zonal schemes are defined by a single perimeter. Motorists pay a charge not only to enter or exit a zone but also to travel within it. However, they pay only once daily regardless of how often they cross in or out. The choice between cordons and zonal schemes has not been extensively studied, and practical experience is limited since the Stockholm and Singapore cordons and the London zonal charge are the only examples. Charging tolls on only part of the road network can induce drivers to reroute trips onto untolled links so that congestion, accidents, and pollution get displaced rather than reduced. This suggests that road pricing has scale economies with respect to network coverage.[6] But scale diseconomies prevail for links in a series because tolling one link reduces traffic on upstream and downstream links. In the case of a single cordon enclosing a city center, the benefits tend to be maximized at an intermediate size.[7]

Satellite-based road pricing, whereby drivers are charged a few cents for each kilometer driven, is used in Germany and Slovakia to charge trucks, and trials for charging cars have been conducted in Europe and the United States. Although satellite-based systems have high fixed costs and require vehicles to be equipped with on-board units, they have an advantage over cordons and other conventional schemes in covering large road networks. Moreover, scale economies can be exploited with satellite systems if they are deployed in multiple cities or countries.

Pricing Only Some Users

For practical or political reasons, it may be necessary to exclude some user groups from paying tolls. However, exemptions undermine the efficiency of a scheme if the marginal benefits of travel are lower for exempt users than for others. For example, on most toll roads around the world, motorcycles pay no tolls, although they can contribute significantly to congestion (Lee et al. 2010) and emissions (Musso et al. 2010). Taxis are exempt from the London congestion charge (LCC). But because taxis and cars are highly substitutable in London, the number of taxi trips increased considerably following implementation of the congestion charge.

Pricing Public Transport

Public transport has scale economies in service frequency, spacing of stops, density of lines, and service reliability. Were there no road congestion, marginal cost pricing would call for setting public transport fares below average cost (Mohring 1972). That is, fares would include a component equal to the marginal cost of service provision as well as a subsidy reflecting the positive demand externalities of a bus ride. Since buses contribute to traffic congestion, and riders impose crowding costs on each other, fares should also include a congestion charge.

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[6] This has been shown in simple models (e.g., Verhoef, Nijkamp, and Rietveld 1996).

[7] If a cordon encloses a very small area, it has little effect since most travel occurs outside it. A cordon also has little effect if it encloses a very large area since most travel then occurs inside it.

However, second-best pricing calls for a subsidy if car congestion is underpriced, and the subsidy may outweigh the transit congestion charge. Parry and Small (2009) conclude that fares below 50 percent of average costs are justified for Washington, DC; Los Angeles; and London in the absence of congestion charges.

Nevertheless, discounting fares deeply or making public transit free has several disadvantages (Newbery 1990). Subsidies must be financed by distorting taxes, and riders attracted by the low fares may be making new trips rather than switching from cars. For short distances, new riders may switch from bicycling and walking (Van Goeverden et al. 2006). Because suburban rail can be a complement to car travel, lowering rail fares can result in higher externalities due to additional "kiss-and-ride" and park-and-ride trips. Conversely, imposing tolls on cars can depress the complementary usage of public transport and undermine its scale economies.

Investment in Public Transport

Investment in public transport complements road pricing since it helps accommodate those travelers who stop driving, and models suggest that adding public transport capacity boosts the benefits of road pricing (Small 2004; Ahn 2009). Given scale economies in public transport, investment improves service quality, which magnifies the modal shift. For buses, the modal shift can be even bigger because removing cars from the road allows buses to travel faster.

Nevertheless, several factors limit the scope for reducing automobile congestion through investments in public transport. Construction of park-and-ride facilities may be necessary to provide access to public transport. Metro and light rail transit systems are expensive to expand and often face space constraints. Bus service is generally much cheaper, but buses contribute to automobile congestion unless they are given new, separate lanes. Otherwise, converting existing lanes to bus-only access uses valuable road space and can increase car congestion if the reduction of congestion from segregating buses and cars is more than offset by the reduction of lane capacity for cars. The limitations of using public transit improvements to reduce emissions are discussed in the next section.

Experience with Urban Road Pricing Schemes

On most of the world's toll roads, toll revenues are used either to cover maintenance and amortize construction costs or to make a profit for private operators. The use of road pricing as a tool to manage demand is relatively rare. High occupancy toll (HOT) lanes dominate in North America. The only network- or area-based urban congestion pricing schemes are in Singapore and Europe. This section first reviews the Singapore, London, and Stockholm congestion pricing schemes and the Milan EcoPass, a zonal scheme designed to reduce pollution (see Table 1 for a summary of these programs). This is followed by a review and discussion of simulation studies showing that the potential for environmental taxes and public transport pricing and investment to alleviate congestion and pollution is limited.

Singapore's Congestion Pricing Programs

In 1975, Singapore launched the world's first congestion pricing program, a cordon scheme called the Area License Scheme (ALS), which was designed to control morning traffic entering the central business district (Gómez-Ibáñez and Small 1998; Santos, Li,

Table 1 Summary of selected road pricing schemes

	Singapore's ERP (successor to ALS 1975–1998)	**LCC**	**Stockholm congestion charge**	**Milan Ecopass**
Inception	1998	February 2003	Trial: January 3–July 31, 2006 Permanent: August 1, 2007	January 2008
Tolled area or infrastructure	Expressways, arterial roads, and cordon charges for three restricted zones around CBD	Original: 21 km^2 area around city centre, extended to west from February 2007 to December 2010	Cordon around 30 km^2 inner city area (eighteen control points)	Restricted zone of 8 km^2 in city center
Time variation	CBD 7:30–10 a.m., 12–8 p.m.; expressways: 7:30–9:30 a.m.; charges change in five- or thirty-minute steps; charge levels reviewed quarterly	Original: Flat charge of £5 from 7:00 a.m. to 6:30 p.m. on weekdays; no charge on weekends or holidays. Present: Charge of £10 from 7:00 a.m. to 6:00 p.m., weekdays	Variable: 10, 15, or 20 Swedish kroner, depending on time of day from 6:30 a.m. to 6:30 p.m.; daily maximum of 60 kroner; no charge on weekends, holidays, or day before holidays	Flat charge 7.30 a.m. to 7.30 p.m. on weekdays. €2 to €10 depending on engine emissions standard. Most-polluting vehicles banned from October 15 to April 15
Toll differentiation by vehicle and user characteristics	Differentiated by six vehicle types; exemption for police cars, ambulances, fire engines	Exempt: Blue badge holders, alternative fuel vehicles that meet strict emissions criteria, electrically propelled vehicles, vehicles with more than nine seats, motor tricycles, roadside recovery vehicles, breakdown vehicles. Discounts: 90% for residents, 12.5% for fleets, various for monthly and annual payments	Exempt: Buses, taxis (abolished after trial), emergency vehicles, electric and hybrid cars, traffic between Lidingö island and rest of county that spends less than thirty minutes crossing the charging zone. Discounts: none.	Exempt: Various vehicle categories. Also clean conventional fuel vehicles and several types of alternative fuel vehicles. Discounts: 50% rebate for first fifty entries, 40% rebate for second fifty entries. Residents of restricted zone can buy annual pass for 25× cost of daily charge

Continued

Table 1 *Continued*

	Singapore's ERP (successor to ALS 1975–1998)	LCC	Stockholm congestion charge	Milan Ecopass
Supplementary measures	Multiple vehicle ownership taxes, fuel taxes, parking fees, road expansion, mass rapid rail, buses, taxis, park and ride, car cooperatives, signal timing	Increase in bus service, retiming of traffic signals	New bus lines, extension of existing bus, metro, and rail service, new and improved park-and-ride facilities	New bus lanes, revised traffic directions, and reduced illegal and on-street parking

Source: Adapted from De Palma, Lindsey, and Proost (2007) and Lindsey (2007) with additions from Eliasson et al. (2009), Rotaris et al. (2010), Federal Highway Administation (2009), Singapore's Land Transport Authority (http://www.lta.gov.sg/motoring_matters/index_motoring_erp.htm), and Transport for London (http://www.tfl.gov.uk/roadusers/congestioncharging/default.aspx).

Notes: U.S. dollar (USD) exchange rates as of August 2, 2010 (http://www.oanda.com/currency/converter)—Pound sterling, USD 1.56852; Swedish kroner, USD 0.13880; Euro, USD 1.30466. CBD, central business district.

and Koh 2004).[8] Cars with four or more passengers were exempt from the charge. While flows during the morning charge period dropped greatly, this was due mainly to rescheduling of trips and rerouting of through traffic around the zone (Chin 2005). The cost to automobile commuters of rescheduling their trips may have exceeded the value of their travel time savings (Wilson 1988). In addition, bus riders experienced an increase in travel times as greater passenger loads resulted in longer stops (Wilson 1988). The effect of the ALS on air pollution is unclear because the monitoring period was short, and there was inadequate control for other determinants of air quality (Chin 1996). In 1998, the ALS was replaced by the current ERP scheme (see Table 1 and Chew 2008). Olszewski and Xie (2005) concluded that the time structure of tolls is effective in controlling congestion. Although ERP appears to be an operational and travel demand management success, there has been no benefit–cost analysis of the program.

London's Congestion Pricing Program

The LCC was introduced in 2003 and imposed a flat £5 zonal fee (see Table 1). A flat fee was chosen because travel speeds in the city center were constant during the day (Leape 2006). In 2005, the fee was raised to £8, and in 2007 the charging period was shortened to end at 18:00 hours and the charging zone was expanded to the west.[9] The assessment of impacts here focuses on changes in travel conditions during the first year or two since this provides the best indication of the effects of the charge. An early analysis of the LCC found that just over half of the deterred car trips shifted to public transport, around a quarter diverted around the charging zone, 10 percent shifted to taxis, and 10 percent were either rescheduled outside charging hours or canceled (Leape 2006). As shown

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[8] An evening charge was introduced in 1988.

[9] The Western Extension was abolished on January 4, 2011. The daily charge for the remaining zone was also increased to £10 (see http://www.tfl.gov.uk/roadusers/congestioncharging/17094.aspx).

Table 2 Impacts of LCC, Stockholm congestion trial, Milan EcoPass

	London	**Stockholm congestion trial**	**Milan Ecopass**
Congestion			
Traffic volumes	−34% cars, +22% taxis, −12% all vehicles[a]	−22% across cordon, −16% within cordon[f]	−12.3% in RZ, −3.6% outside[i]
Travel times	−30% congestion delay as of mid-2005[a]	Congestion delays dropped 1/3 to 1/2 on arterials, lesser reductions inside cordon[f]	
Speeds	+17% in RZ, averaged over whole day[a]		+4% in RZ for private vehicles, +7.8% for buses[h]
Accidents	−2% to −5% for personal injuries[b]	−5% to −9% injuries[f], −3.6% accidents[g]	−20.6%[i]
Emissions			
NO_x	−12%[c,d]	−8.5%[g]	−14%[h]
PM10	−12%[c,d]	−13%[h]	−19%[h]
PM			−18%[i]
Air-borne pollutants		−10 to −14%[g]	
CO2	−19%[c,d]	−14%[f]	−15%[h]
Public transport [person trips]	+30% within RZ during first two years[e]	+4.5% across cordon[g]	+7.3% surface PT[i], +9.2% exits in RZ[h]

Sources: [a]Leape (2006), [b]Transport for London (2005), [c]Transport for London (2004), [d]Beevers and Carslaw (2005), [e]Transport for London (2007), [f]Eliasson et al. (2009), [g]Eliasson (2009), [h]Rotaris et al. (2010), [i]AMMA (2008).

Notes: The effect of the Stockholm congestion tax on accidents was estimated using traffic safety relationships developed by the National Road Administration and accounting for the effect of higher average speeds on accident frequency and severity (Eliasson 2009). Reductions in pollution in Stockholm were estimated using air quality dispersion models (Eliasson 2009). RZ, restricted zone, PT, public transport.

in Table 2, taxi vehicle kilometers increased 22 percent and trips by bus increased 30 percent. This result is driven partly by an increase in bus service and partly by an increase in bus speeds and better adherence to timetables. The 2–5-percent drop in accidents occurred during a period of steady general decline in accidents, making it difficult to determine accurately the effects of the congestion charge. Although emissions of nitrous oxide (NO_x) and PM10 dropped by 12 percent in the charging zone, emissions increased by about 1.5 percent on the inner ring road that forms the perimeter of the charging zone, indicating that there was some displacement of emissions (Beevers and Carslaw 2005). The reductions in NO_x and PM10 were caused partly by drops in vehicle numbers and partly by increases in vehicle speeds due to less stop-and-go driving and queuing at junctions (Banister 2008). Bus kilometers increased in the zone, but, thanks to new engines and particle traps, bus emissions did not increase appreciably.

Prud'homme and Bocarejo (2005) argue that the LCC is not cost effective, but Mackie (2005) claims that they underestimate the value of travel time savings and the benefits from improved bus service and reliability. Santos (2008) reports that in its annual monitoring report, Transport for London (2007) estimated the net benefit of the original scheme at £112 million. As shown in Table 3, time savings and reliability benefits for drivers, net of the costs of trips foregone by deterred drivers, account for about 70 percent of the total benefits. Benefits for public transport users comprise a majority of the balance. Benefits of local air pollution improvements were not calculated.

Electric and alternative fuel vehicles are exempt from the LCC, but otherwise the LCC does not feature emissions-based pricing. However, on January 4, 2011, a "Greener Vehicle Discount" scheme was introduced that provides a 100-percent discount to all cars that emit less than 100 g/km of CO_2 and meet the Euro 5 standard for air quality (see http://www.whatgreencar.com/congestioncharge.php).[10] In addition to this new measure, a low emission zone (LEZ) was created in 2008 to cut NO_x and PM10 (see http://www.tfl.gov.uk/roadusers/lez). The LEZ covers most of Greater London and affects vehicles weighing over 1.205 tons with diesel engines that exceed Euro III emissions standards.[11] A daily fee of £200 is paid to drive these vehicles in the LEZ at any time.

Stockholm's Congestion Pricing Program

Stockholm's congestion pricing program, which targets a single cordon or zone around the central city with eighteen control points, was introduced as a trial in 2006 and made permanent in 2007 following a successful referendum (see Table 1). The impacts of the congestion charge in Stockholm were similar to those in London (Table 2), with travelers adapting to the charge by making fewer trips and changing destinations, mode, and route. Surprisingly, there was little departure-time shifting despite the time variation in the charge. Substantial health benefits are expected from pollution reductions because high population densities in the inner city cause a high level of aggregate exposure to pollution (Eliasson et al. 2009).

Before the trial began, additions and improvements were made to Stockholm's bus, metro, and rail service and to park-and-ride facilities. Due to limited rail track capacity, it was not possible to significantly increase the number of peak-period trains (Kottenhoff and Brundell Freij 2009), and thus most of the investment was in buses. However, the public transport improvements did not boost ridership significantly before the trial (Kottenhoff and Brundell Freij 2009). During the trial, most people on work and school trips who stopped driving switched to public transport. But the 4.5-percent increase in public transport ridership (see Table 2) accounted for less than half of the added seats. Crowding increased in underground trains but fell in commuter trains.

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[10] New vehicles sold in the European Union have been subject to a series of progressively more stringent emission standards. The standards differ for diesel and gasoline engines and for passenger cars, light commercial vehicles, and large goods vehicles. The Euro 5 standard for passenger cars, which was introduced in 2009, specifies limits on emissions of carbon monoxide (CO), NO_x, hydrocarbons (HC), and particulate matter (PM).

[11] The Euro III standard for large goods vehicles, which was introduced in 1999, specifies limits on emissions of CO, NO_x, HC, PM, and smoke.

Table 3 Benefits and costs of LCC, Stockholm congestion trial, Milan EcoPass

	London[a], £ million (2005)		**Stockholm congestion trial[b], SEK million (2006)**		**Milan Ecopass[c], € million (2008)**	
Gross benefits	230		938		30.2	
Total costs	163		284		14.5	
Net benefits	67		654		15.7	
Setup costs	170		1,900		7.0	
Decomposition of benefits						
Time savings and reliability benefits	185		614		12.8	
Deterred drivers	−25		−74		−0.2	
Subtotal (all drivers)	160	69.6%	540	57.6%	12.6	41.7%
Public transport	42	18.3%	−15	−1.6%	8.6	28.5%
Reduced accidents	15	6.5%	125	13.3%	6.6	21.9%
NO_x + PM10			22	2.3%	1.8	6.0%
Reduced CO_2 emissions	3	1.3%	64	6.8%	0.6	2.0%
Other resources	10	4.3%				
Premium on government revenues			202	21.5%		

Sources: [a]Leape (2006), [b]Eliasson (2009), [c]Rotaris et al. (2010).

Notes: Percentage figures that appear under "Decomposition of benefits" are percentages of gross user benefits. U.S. dollar (USD) exchange rates as of August 2, 2010 (http://www.oanda.com/currency/converter)—Pound sterling, USD 1.56852; Swedish kroner, USD 0.13880; Euro, USD 1.30466.

As shown in Table 3, Eliasson (2009) presents a relatively comprehensive benefit–cost analysis of the trial, estimating the annual benefits net of operating costs to be SEK 654 million and the investment and startup costs to be SEK 1.9 billion. Unlike the London program, the benefits of the Stockholm scheme include a premium on net government revenue, which accounts for more than 20 percent of the total benefit. The benefits of reduced travel times and increased reliability for cars are less dominant than for London, although they still account for more than half of the benefits. Indeed, the time gains amount to 70 percent of revenue, which is very high compared to the predictions of most analytical studies (Eliasson 2009). Eliasson (2009) attributes this result partly to the large numbers of drivers with high values of time and partly to the gains to those outside the cordon who benefit from a reduction in congestion from traffic crossing the cordon. Public transport users are estimated to be slightly worse off because of more crowded subways.[12]

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[12] The benefits of increased bus speed and punctuality are excluded from the analysis.

Milan's EcoPass Program

Milan's EcoPass, which was introduced on a trial basis in January 2008, has a main goal of reducing high levels of PM10 and other pollutants. As shown in Table 3, preliminary estimates, based on the first eleven months of the program, indicate a net annual benefit from EcoPass of €15.7 million (Rotaris et al. 2010). Benefits accruing to drivers account for 42 percent (smaller than for the London and Stockholm programs), while those accruing to public transport users (28 percent) and those due to accident savings (22 percent) are much larger than for the London and Stockholm programs. Reductions in pollution (6 percent) are larger than for Stockholm, while reductions in CO_2 emissions (2 percent) are smaller.

Assessments of Environmental Benefits and Public Transit Improvements

Real-world experience with the London, Stockholm, and Milan schemes suggests that the environmental benefits of road pricing are limited, amounting to only a small fraction of the benefits from drivers' time savings. Most simulation studies have reached similar conclusions. In countries with high fuel taxes, such as the United Kingdom, it has been found that fuel-related externalities are actually overpriced (Small and Parry 2005), which means that adding an environmental tax to a congestion charge would reduce welfare (Santos 2008). Santos and Newbery (2001) examined combined congestion and environmental pricing for nine pollutants in eight British towns and concluded that the environmental benefits are unlikely to reach 10 percent of the benefits from congestion relief. Hensher's (2008) model for Sydney predicts reductions in CO_2 emissions of 5 percent or less from a user charge of ten cents per kilometer on the main road network. Tolling roads selectively is less effective for two reasons. First, drivers have more options for rerouting to untolled roads that entail greater travel distances. Second, those willing to divert to untolled roads tend to have lower values of time, and correspondingly lower incomes and older vehicles that are heavily polluting, so that they generate substantial additional emissions from the extra distance traveled. Daniel and Bekka (2000) find that if tolling is applied to all roads, environmental benefits reach 30 percent of the benefits from time savings. Mitchell, Namdeo, and Milne (2005) draw qualitatively similar conclusions for cordon tolling. They find that the spatial redistribution of emissions is more pronounced for a single cordon than for a double cordon. This is because a double cordon charges more uniformly over space and is more effective at suppressing the rerouting of trips.

The environmental effects of tolling can also depend on the technology used. At conventional toll plazas, drivers have to stop to pay, which can result in long waits. Emissions occur while vehicles are decelerating, idling, and then accelerating back to highway speed. Electronic toll collection (ETC) does not require drivers to stop or even slow down. Thus, converting toll facilities to ETC can reduce emissions. Lin and Yu (2008) found that such a switch results in substantial reductions in CO concentrations and diesel PM emissions, and Currie and Walker (2009) found that there were reductions in premature and low-weight births of about 11 percent.

Simulation models have also found that improvements in public transportation pricing and investment have limited benefits. Using a model of Brussels, Proost and Van Dender

(2008) find that optimizing public transport fares and service frequencies yields only 7 percent of the welfare gain achieved from the first-best policy of pricing both public and private modes of transportation and expanding public transport. Parry and Timilsina (2010) study road pricing as an instrument for addressing Mexico City's severe congestion and air pollution problems. They find that tolling microbuses yields only 16 percent of the gain achieved from tolling cars even though a microbus creates more congestion than a car, and collectively microbuses account for 28 percent of trips made under the status quo. The reason for this result is that tolling microbuses induces a large modal shift to cars, which are severely underpriced. Thus, the microbus toll will be more beneficial if automobiles are tolled as well. Anas and Timilsina (2010) study the effectiveness of improving bus service quality in Beijing's core as a tool for offsetting the increased CO_2 emissions from road expansions. They conclude that the policy is quite ineffective, with one reason being the low cross-elasticity of bus travel time with car traffic and the other being that improving bus travel times attracts additional riders who previously walked and bicycled. This causes road congestion and emissions to remain high.

Distributional Impacts and Public Acceptance of Road Pricing

Who are the winners and losers from road pricing policies? This question is important because road users are highly diverse and a road pricing scheme will be politically acceptable only if it gets sufficient public support. To address heterogeneous preferences, policies can be designed that include features such as differential pricing, express lanes, carpool discounts, and high occupancy car lanes and bus lanes (Verhoef and Small 2004; Small, Winston, and Yan 2006). However, even the most sophisticated and sensitive policy designs will create some losers and thus induce opposition. In fact, lack of public acceptance has been the most important barrier to road pricing schemes. For example, cordon schemes for Edinburgh and Manchester were rejected by public referenda in 2005 and 2008, respectively. In 2007, an online petition against road pricing convinced the UK government to shelve plans for a nation wide scheme. A combined cordon and zonal scheme for Manhattan was stopped by the New York state legislature in 2008, while in Chicago, local government leaders have shown no real interest in road pricing. Equity issues as well as ways to increase public acceptance of road pricing are discussed below.

Equity Issues

The literature on equity distinguishes between vertical and horizontal equity (e.g., Santos and Rojey 2004; Ecola and Light 2009). In road pricing studies, vertical equity is usually defined in terms of personal or household incomes. Most studies have found that road pricing is regressive in terms of the distribution of personal benefits from congestion relief net of the toll paid. However, the ultimate distribution of net benefits depends crucially on how the toll revenues are used because the revenues are typically much larger than the efficiency gains. Revenues can be used to expand road capacity or invest in public transport, to reduce public transit subsidies or income taxes, and so on. Mayeres and Proost (2001) and others have shown that the net benefits of a road pricing scheme vary widely across these revenue options. Horizontal equity is defined in terms of mobility or accessibility, which depends on location—especially for road pricing schemes with lumpy charges such as cordons (discussed below). Several studies have addressed the equity dimensions of road pricing according to where people live (e.g., Santos and Rojey 2004; Graham et al. 2009; Karlström and Franklin 2009), but the inequity arising from differences in pollution exposure has been largely ignored.

Congestion Tolls and Equity

In one of the first case studies of road pricing and equity, Small (1983) assesses the equity impacts of congestion tolls at a single tolled facility (an expressway in the San Francisco Bay Area) that is used by cars and buses. He finds that high-income travelers gain from the tolls because they value time savings highly relative to the toll they pay. Low-income travelers may also benefit if enough of them use public transport because with fewer cars on the road, buses can travel more quickly. Middle-income individuals who drive are the most likely losers because they are attached to their cars but place a lower value on time savings than on the toll they pay.

Cordon Pricing and Equity

In a study of a cordon toll of morning commuters entering the central region of Paris, Bureau and Glachant (2008) find that all income quintiles become worse off without toll revenue recycling. This study also demonstrates that the availability of public transit limits the welfare losses of low-income groups. Santos and Rojey (2004) find that in several UK towns cordon pricing can be progressive, neutral, or regressive depending on the spatial distribution of income and the locations of residences, workplaces, and other destinations. Since income distributions and origin–destination patterns can vary significantly between cities and regions, equity has to be measured on a case-by-case basis, a point also made by Ecola and Light (2009). Fridstrom et al. (2001) find that small cordons tend to hurt people living inside because most of their destinations are outside and they have to cross the cordon to reach them. People living outside are less reliant on the few destinations inside, and they can easily circumnavigate the cordon to go elsewhere. In contrast, large cordons tend to be more harmful for people living outside rather than inside the cordon. Using a computable general equilibrium model (see Anas and Liu 2007) of a metropolitan region, Hiramatsu (2010) analyzes the effect of a hypothetical cordon line placed around Chicago's downtown and finds that a cordon toll of $11 per inward crossing maximizes toll revenue but reduces the utility of each income quartile. However, when the toll revenue is distributed equally among all residents regardless of income, then aggregate welfare increases, provided the marginal rate of substitution between commuting time and disposable income is sufficiently high.

Equity Impacts of Stockholm's Congestion Charge

Thus far the studies on equity and road pricing reviewed here have been based on hypothetical pricing schemes. Karlström and Franklin (2009) estimate the distributional impacts of the Stockholm congestion charging trial by segmenting the population in several ways. They find that those traveling by car experienced a mean annual welfare loss of SEK 376. Car users who paid the toll incurred a more substantial average loss of SEK 1840, while all remaining travelers gained SEK 69 on average. Public transit users as a group incurred a small loss of SEK 27 due to a slight increase in crowding aboard public transit vehicles. All five income quintiles incurred a welfare loss. However, in contrast to Small's finding for the single facility in San Francisco, here the middle-income quintile of travelers lost the least. Karlström and Franklin attribute this surprising result at least partly to differences among quintiles in the share of household members who drove and crossed the cordon.

Impacts of Road Pricing on Businesses

Businesses located in or near tolled areas are affected by road pricing policies and can be a powerful lobby against tolls. Thus, it is important to examine the impact of road pricing schemes on businesses. According to Chin (2000), retailers and wholesalers in Singapore benefited from improved speeds under the original ALS. No systematic assessment of the effects of the current ERP appears to have been undertaken. Quddus, Carmel, and Bell (2006) assess the effects of the LCC on sales of John Lewis stores on Oxford St. and on retailers within the charging zone. They find a negative and statistically significant effect for John Lewis but none for central London retailers overall. Daunfelt, Rudholm, and Rämne (2009) report no measured effect on retail markets in Stockholm from the congestion charging trial. Commercial vehicles, however, appear to have been made worse off in both London and Milan. According to Santos (2007), the generalized cost of travel for vans and trucks in London increased eighteen pence per kilometer. Costs for freight transporters in Milan have increased because of the high environmental charge imposed on trucks (Rotaris et al. 2010).

Measures to Enhance Public Acceptance of Road Pricing

To address the distributional impacts of road pricing and increase its acceptance by the public, some cities/urban areas have introduced discounts or exemptions for specific groups. For example, in London, discounted charges and exemptions are used together with quantity discounts for fleets and for those drivers making monthly and annual payments. However, while these practices may increase acceptance by those that benefit from them, they undercut efficiency by departing from marginal social cost pricing. Some alternative approaches that increase public acceptance while maintaining efficiency are discussed below. This is followed by a brief discussion of how public attitudes toward road pricing appear to change over time.

Package Approach

A flexible and widely supported approach to enhancing both public acceptance and efficiency is to combine tolls with a package of nonpricing measures. For example, in addition to the ERP, Singapore has adopted numerous pricing and nonpricing measures, including sticks, such as ownership taxes, fuel taxes, and parking fees, as well as carrots, such as building roads and investing and improving bus, rail, and taxi services (Chin 2000; Santos, Li, and Koh 2004). In preparation for the Stockholm trial, public transport services were improved by creating new bus lines, expanding capacity of underground and commuter train lines, and building new park-and-ride facilities (Eliasson et al. 2009). In 2007, the U.S. Department of Transportation launched an Urban Partnership Program that encourages cities to adopt a comprehensive approach called the Four-T strategy: Tolling, Transit, Telecommuting, and Technology (http://www.upa.dot.gov), in which Miami, Minneapolis/St. Paul, San Francisco, and Seattle are currently participating.

Use of Revenues

The use of toll revenues can strongly affect the distributional impacts, and hence the acceptance, of road pricing. Kockelman and Kalmanje (2005) propose a scheme they call credit-based congestion pricing, whereby each month aggregate toll revenues net of administration costs would be returned uniformly to adult residents or owners of registered vehicles in a designated region. Earmarking revenues for local public transportation, and possibly for roads and infrastructure for pedestrians and bicyclists, also has public support. Such earmarking is required by law in London and Stockholm, and for some projects in the United States funded by the Value Pricing Pilot Program (http://www.fhwa.dot.gov/policy/vppp.htm). One advantage of earmarking revenues for investment in transport infrastructure is that it is durable and irreversible, whereas the use of revenues to reduce fees or income taxes is viewed as easily retractable.

Public support for road pricing can be boosted not only by earmarking revenues for public transportation but also by improving service before charging begins. Such a strategy will be more effective if the improvements are presented as part of the road pricing package. A failure to make this connection contributed to the vote against the proposed Edinburgh cordon toll in 2005 (Laird, Nash, and Shepherd 2007). In addition, in Hong Kong the opening of the Mass Transit Rail alleviated congestion and reduced the perceived need for ERP (Ison and Rye 2005). However, earmarking revenues to public transit worked well in both London and Stockholm.

Changes in Attitudes

Studies indicate that attitudes toward road pricing improve after programs are implemented, suggesting that people become more favorably inclined toward road pricing once they experience its benefits. This change in attitudes was observed in London, Stockholm, and Milan, as well as with the Norwegian toll rings and the HOT lane facilities in the United States (Schade and Baum 2007; Zmud 2008). However, while Stockholm County residents became more supportive of the program, the number who thought congestion and air quality would improve did not increase appreciably during the trial. This is consistent with the argument of Harsman and Quigley (2010) that the voting to make the congestion pricing program permanent was influenced by political ideology (i.e., voter affiliation with the positions of the political parties competing in the election). According to Winslott-Hiselius et al. (2009), people changed their attitudes toward the Stockholm program as it became clear that the congestion charge would likely become permanent. Schade and Baum (2007) report similar results for Dresden. This evidence suggests that it is best to hold a referendum on road pricing once a trial has been implemented, as in Stockholm, rather than before implementation of any program, as in Edinburgh and Manchester.

Conclusions

Congestion, accidents, and other externalities of urban road transportation impose substantial social costs. Road pricing has been promoted by economists as a way to force motorists to confront these costs. This article has reviewed road pricing theory and experience with past and present urban road pricing schemes, as well as the literature on the potential benefits of road pricing, its distributional impacts, and how it can be made more acceptable to the public.

Summary of Findings

In the introduction, we identified four general issues related to urban road pricing. The results of our review suggest conclusions concerning the first three issues, which we summarize here. We then address the fourth issue below.

First, road pricing schemes have affected traveler behavior in several ways, which are generally consistent with models of travel behavior. Singapore's ERP system, the LCC, and the Stockholm congestion charge were designed primarily to relieve congestion. All three schemes have operated relatively smoothly and induced reductions in congestion. Benefit–cost analyses indicate that for the London and Stockholm schemes, the combined benefits to motorists, public transport users, and the environment exceed system setup and operating costs. No benefit–cost analysis has been conducted for Singapore's ERP. Unlike the other schemes, the main goal of the Milan EcoPass is to reduce pollution. This scheme, too, has resulted in measurable improvements in travel speeds and air quality, and a provisional benefit–cost assessment shows that the scheme is cost effective.

Second, the review indicates that potential congestion relief benefits of road pricing dominate any environmental benefits. Schemes designed for congestion pricing can yield appreciable environmental benefits if they are designed to minimize traffic displacement. However, if cleaner vehicles are exempted from congestion charges, this can undercut congestion relief.

Third, improved public transport and/or significant use of public transport are potentially important policy complements to road pricing. This is because public transportation is a reasonable substitute for the car and thus enables many motorists to avoid tolls by switching from driving. In some cities, it may be possible to exploit scale economies in public transport and expand the quality of service in order to boost ridership further. However, expansion of underground and rail systems is expensive and often constrained by space, and buses are polluting and contribute to traffic congestion unless given separate rights of way. The availability and quality of existing public transport service appear to be more important to the successful introduction of a road pricing scheme than major capacity expansions of public transport. Road pricing is more likely to be accepted in cities with good existing public transport (like Stockholm) because many travelers are transit users who will not pay tolls and stand to gain if the toll revenues are used to improve public transit services.

Prospects for Widespread Implementation of Urban Road Pricing

We conclude with some thoughts on the final issue raised in the introduction—the conditions under which urban road pricing is likely to be both economically attractive and politically feasible, and whether such policies are likely to become widespread in the foreseeable future.

Most attempts at urban road pricing have failed (Richardson and Bae 2008). Large-scale congestion pricing has been implemented only in Singapore, London, and Stockholm. Because in Singapore the government has substantial administrative powers, London and Stockholm would appear to be more relevant as models for how road pricing might be implemented in other cities. What factors have contributed to the success in London and Stockholm, and what lessons have been learned from these programs that could be applied to programs elsewhere?

London has a number of features that worked in its favor: severe traffic congestion, a comprehensive and well-functioning public transport system that already accommodated some 85 percent of travelers entering central London, and the Inner Ring Road, which serves as a natural boundary and conduit for traffic that avoids the charging zone. System designers had a substantial body of research to guide them, and the mayor of London had sufficient powers to forge ahead with road pricing without the need to build a political coalition.

Stockholm also has some features that worked to its advantage. Given its location on a set of islands, it is difficult to expand road capacity to relieve congestion. The island topography made it possible to establish a cordon using only eighteen control points. Jobs are highly concentrated in the city center, which makes a cordon relatively effective for intercepting many trips (Armelius and Hultkrantz 2006). Similar to London, Stockholm has good public transport, and road pricing studies have been conducted for many years, providing a body of research on which to draw.

Could the London or Stockholm model be adopted elsewhere? A collection of authors in Richardson and Bae (2008) address this question for cities in the United States, and their response is largely negative. Congestion in U.S. cities is generally lower than in Europe and less concentrated in city centers. Although 40 percent of trips into the center of New York City are by car, versus 10 percent in London, congestion in New York is much lower. The decentralization of jobs has kept U.S. commuting times remarkably stable as urban sprawl has increased with population growth. Anas (2010) shows that average commuting time increases by only 10 percent as U.S. metropolitan areas double their numbers of workers. Sprawl, like public transit, appears to serve as a safety valve for congestion in a growing urban area. However, sprawl also reduces the viability of public transit.

Road pricing is more likely to be implemented on a wide scale if the external costs of road transportation increase as a fraction of incomes. The prognosis varies by externality. Since the 1970s, advances in emissions control technology have greatly reduced emissions per vehicle kilometer. The costs of local air pollution have also decreased, and the trend is likely to continue despite the fact that population growth and continuing urbanization in some countries are increasing exposure to pollutants. Reductions in greenhouse gas emissions may lag because there are currently no economically viable technologies to reduce CO_2 emissions from carbon-based fuels. Incremental improvements in engine and transmission efficiency and introduction of electric and alternative-fueled vehicles are currently the main supply-side measures for tackling greenhouse gas emissions (TR News 2010). However, given current shadow prices for greenhouse gas emissions, climate change is a minor component of the external costs of road transport (Delucchi and McCubbin 2009) and hence does not warrant drastic policy measures, at least not based on a benefit–cost analysis.

The steady decline in accidents per vehicle kilometer in the United States has run up against a trend of increasing total vehicle kilometers traveled. The total number of accidents has remained relatively constant although there has been a sharp reduction since 2005 (Sivak and Schoettle 2010). Congestion is the biggest externality of road travel, and thus the long-term outlook for congestion has the greatest consequences. Space, environmental, and budgetary constraints limit road construction. Total vehicle kilometers traveled continue to grow, especially in developing countries such as China and India, where car ownership rates are increasing rapidly. Automated freeways would greatly increase effective road capacity, but they are not likely to be built for some time. Meanwhile, air conditioning, on-board navigation systems, and cell phones make in-vehicle time more productive or enjoyable, which is likely to cause more driving and congestion. High-tech gadgetry may also contribute to more accidents by distracting drivers.

In summary, air pollution and excess fuel use due to congestion diminish as fuel economy improves through technological progress. The climate change externality is the most unpredictable because the social costs of climate change are so uncertain, but current estimates suggest that climate change contributes only a small fraction of external road transportation costs. Unless more highways are built, the congestion costs that now dominate external costs might become even more dominant. Yet, building roads encourages more driving. Thus, it appears that only road pricing has the potential to manage congestion in an economically efficient way.

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