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TRAFFIC CONGESTION PRICING METHODS AND TECHNOLOGIES

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Abstract: This paper reviews the methods and technologies for congestion pricing of roads. Congestion tolls can be implemented at scales ranging from individual lanes on single links to national road networks. Tolls can be differentiated by time of day, road type and vehicle characteristics, and even set in real time according to current traffic conditions. Conventional toll booths have largely given way to electronic toll collection technologies. The main technology categories are roadside-only systems employing digital photography, tag and beacon systems that use short-range microwave technology, and in vehicle-only systems based on either satellite or cellular network communications. The best technology choice depends on the application. The rate at which congestion pricing is implemented, and its ultimate scope, will depend on what technology is used and on what other functions and services it can perform. Since congestion pricing calls for the greatest overall degree of toll differentiation, congestion pricing is likely to drive the technology choice.

Key words: Road pricing; Congestion pricing; Electronic Toll Collection technology

Codes JEL: D62, R41, R48

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1 INTRODUCTION

Traffic congestion is common in large cities and on major highways and it imposes a significant burden in lost time, uncertainty, and aggravation for passenger and freight transportation. The European UNITE project estimated the costs of traffic congestion in the UK to be £15 billion/yr. or 1.5% of GDP (Nash *et al*., 2003). For France and Germany the estimates were 1.3% and 0.9% of GDP respectively. The Texas Transportation Institute conducts an annual survey of traffic congestion in major US cities. According to the 2009 report, in 2007 congestion caused an estimated 4.2 billion hours of travel delay and 2.8 billion gallons of extra fuel consumption with a total cost of $87 billion (Schrank and Lomax, 2009).

Most of the costs of traffic congestion are borne by travelers collectively, but because individual travelers impose delays on others they do not pay the full marginal social cost of their trips and therefore create a negative externality. The standard economic prescription to internalize the costs of a negative externality is a Pigouvian tax. In the first edition of his textbook, *The Economics of Welfare*, Pigou (1920) himself argued for a tax on congestion and thereby launched the literature on congestion pricing. Most economists have supported congestion pricing although many have been concerned about the details of implementation (Lindsey, 2006). Congestion pricing has a big advantage over other travel demand management policies in that it encourages individuals and firms to adjust all aspects of their behaviour: number of trips, destination, mode of transport, time of day, route, and so on, as well as their long-run decisions on where to live, work and set up business.

For decades congestion pricing remained largely an ivory-tower idea, but interest gradually spread outside academia and congestion pricing has come into limited practice. The main operating schemes are High Occupancy Toll (HOT) lane facilities in the US, the London Congestion Charge, the Stockholm cordon charge[1], and Singapore's Electronic Road Pricing system. Few cost-benefit analyses of these (or other) congestion pricing systems have been undertaken. However, the limited evidence suggests that well-designed schemes can yield significant net economic benefits. Small et al. (2006) estimate the benefits from tolling a two-

[1] According to Swedish law the congestion charge is a tax, but it will called a charge or toll in this review.

lane facility similar to the State Route 91 (SR-91) HOT lanes in Orange County, California.[2] Optimal tolling of both lanes yields a welfare gain of nearly $3 per trip, while operating one lane as a HOT lane and leaving the other lane free yields a still appreciable gain of $2.25 per trip.

The London Congestion Charge has been closely monitored since it was introduced in 2003. The fifth annual report (Transport for London, 2007) estimated the gross annual benefits of the original scheme at £200 million ($326 million)[3] and the total costs at £88 million ($143 million), resulting in a net benefit of £112 million ($183 million) and a benefit-cost ratio of 2.27.[4] Stockholm's congestion charge began as a seven-month Trial in 2007 and, after a successful referendum, became permanent in 2007. Based on results of the Trial, Eliasson (2009) estimated the annual benefits net of operating costs to be about SEK 650 million/year ($92 million) and investment and startup costs of about 1.9 billion SEK ($268 million) yielding a social surplus pay-off time of only four years. Singapore's Electronic Road Pricing has not been put to a comprehensive cost-benefit test, but the system is widely held up as a successful model.

The Netherlands is developing a national distance-based system of tolls to control congestion and emissions and several other countries are also considering national schemes — in part to internalize congestion and other traffic externalities. However, despite the apparent success of existing schemes, and plans to establish more, congestion pricing continues to be a hard sell. Several major proposals have recently been scuttled by public or political opposition. Cordon tolling schemes for Edinburgh and Manchester were rejected by public referenda in 2005 and 2008, respectively. An online petition to the UK government in early 2007 attracted more than 1.8 million signatures against road pricing, and effectively put an end to plans for a national

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[2] HOT lanes run in parallel with lanes that are not tolled. High Occupancy Vehicles (HOVs) can use the HOT lanes without paying. The occupancy requirement is usually either two people (HOV2+) or three people (HOV3+) as on SR-91.

[3] This information is taken from Santos (2008).Throughout the paper foreign currency amounts are converted to US dollars at August 29, 2009 exchange rates.

[4] The congestion charging zone was extended to the west in 2007. In an ex ante analysis Santos and Fraser (2006) determined that the Western Extension fails a cost-benefit test. To the best of our knowledge an *in medias res* cost-benefit analysis of the extension has yet to be done.

scheme in the UK for the time being. And a cordon toll plan for New York City was stopped by the New York state legislature in April 2008 when it declined to vote on the proposal.

These setbacks illustrate the difficulties of designing congestion pricing schemes that are both efficient and publicly acceptable. Much has been written recently about road pricing in general, and congestion pricing in particular, and it is useful to delineate the bounds of this review as well as to provide a few references for material that is not covered. As the title of the review indicates, it concerns ways in which traffic congestion pricing can be implemented and the technologies available for doing so. Considerable attention is given to comprehensive distance-based pricing because it appears to offer substantial potential benefits while also posing considerable technological challenges.

Due to space limitations a number of topics related to traffic congestion pricing are excluded from the review including parking congestion and parking pricing[5], pricing of road emissions[6], the use of congestion pricing revenues[7], and the role of congestion tolls in guiding efficient investments.[8] Slot-based reservation systems in which drivers book trips in advance are ignored[9] as are pricing instruments that may reduce congestion but are not designed to do so such as fuel taxes, vehicle ownership taxes, vehicle registration fees, and Pay-As-You-Drive (PAYD) insurance[10]. Public-choice and other institutional considerations are mentioned only incidentally.[11]

The balance of the paper is organized as follows. Section 2 provides a brief summary of the theory of congestion pricing with an emphasis on practical complications. Section 3 describes

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[5] See Shoup (2005), Arnott et al. (2005, Chapter 2) and Arnott (2009).

[6] See Johansson-Stenman and Sterner (1998) and Jensen-Butler et al. (2008).

[7] See De Palma et al. (2007).

[8] See Small and Verhoef (2007, Chapter 5).

[9] See Wong (1997).

[10] See Proost and Van Dender (1998), Parry (2005), and Bordoff and Noel (2008).

[11] Governance is discussed by Sorensen and Taylor (2005), the potential role of the private sector in building and operating toll roads by Gómez-Ibáñez and Meyer (1993) and Small (2008), public acceptability by Schade and Schlag (2003), and equity by Ecola and Light (2009).

methods of congestion pricing as defined by network coverage and how tolls are differentiated by time of day, type of road, and other dimensions. Section 4 describes technologies that are used, or being tested, for congestion pricing and reviews their strengths and weaknesses. Concluding remarks are made in Section 5.

2 THEORY OF CONGESTION PRICING

Although this review is primarily concerned with the methods and technologies for congestion pricing it is useful to begin by summarizing the theory in order to identify the functional requirements of an effective congestion pricing scheme.[12] Following Walters (1961) consider first a single road link. Let Q denote flow on the link measured in vehicles per hour, and $c(Q)$ the generalized cost of a trip on the link (i.e. vehicle operating cost plus travel time cost). The total cost of Q trips per hour is then $TC = c(Q)Q$, the marginal social cost of a trip is $MSC = dTC/dQ = c(Q) + c'(Q)Q$, and the marginal external cost is $MEC = MSC - c(Q) = c'(Q)Q$. The Pigouvian toll is therefore $\tau = c'(Q)Q$.

The Pigouvian toll formula for a single link extends to each link of a road network if all links can be tolled efficiently. Let a denote a link (or arc) in the network, Q_a be the flow on link a, and $c_a(Q_a)$ be the generalized travel cost on link a which is assumed to be independent of flows on other links. As Yang and Huang (1998) show, the Pigouvian toll on link a is simply $\tau_a = c_a'(Q_a)Q_a$, $a \in A$, where A is the set of all links. The toll is a function of flow on the link, but it is independent of travel conditions on other links so that only local information is required to set the toll. Moreover, because tolls are link-based rather than path-based, information is not required about the paths that vehicles follow through the network. This is advantageous in terms of both practicality and privacy since there is no need to track trip origins, destinations, or routes.

The simple Pigouvian theory bypasses many complications that have led to a rich and still expanding literature, but also make practical applications much more challenging than the simple

[12] More comprehensive reviews of the theory are found in Lindsey and Verhoef (2001), Small and Verhoef (2007, Chapter 4), Parry (2008), and Tsekeris and Voß (2008).

theory might suggest. Only some of the more important complications will be identified here.[13] One complication is evident in the single-link formulation from the equilibrium condition that the marginal willingness to pay for a trip equal the cost inclusive of the toll; i.e. $p(Q) = c(Q) + \tau$, where $p(\ )$ is the inverse demand function. To solve for the optimal toll, $\tau = c'(Q)Q$, it is necessary to solve for the equilibrium value of Q when the toll is applied. This requires knowledge of the inverse demand function as well as the link speed-flow curve and the value of travel time (VOT) that underlie the trip cost function $c(\ )$. Despite decades of research, identifying the speed-flow curve is not straightforward — in part because it varies from link to link with lane width, horizontal and vertical alignments and curvature, traffic-control measures and other factors. The relevant VOT is also not a single number but rather an average that depends on the composition of users which in turn varies with the level of the toll, by time of day, and other factors. Values of time can also depend on trip duration, and there is evidence that VOTs are higher under congested than uncongested travel conditions (Calfee and Winston, 1998; Santos and Bhakar, 2006; Hensher and Puckett, 2008).

A second complication is that the congestion externality a vehicle imposes depends on its size, acceleration and braking capabilities, and maneuverability. These factors are typically accounted for by using a Passenger Car Equivalent (PCE) factor (Transportation Research Board, 2000). The PCE of large vehicles is often adjusted to account for hilly terrain, but it can also depend on the proportion of large vehicles in the traffic stream, and a large vehicle can have asymmetric effects on light and heavy vehicles (Peeta et al., 2004).

A third complication is that traffic flows vary greatly by time of day, day of week, and season. Congestion tolls should therefore vary over time as well. Formulating a dynamic system optimum on a road network, deriving tolls that support the optimum, and solving the system of equations numerically remains a challenge despite many years of research.[14]

A fourth complication is that congestion varies not only predictably with recurrent demand patterns but also unpredictably due to accidents, bad weather, special events, transit strikes, and

[13] See Small and Verhoef (2007, Section 4.2) for further detail.

[14] See Carey and Srinivasan (1993), Ghali and Smith (1995), Boyce (2007), Friesz et al. (2008).

other shocks.[15] Tolls should therefore vary according to real-time conditions and they should reflect the value that travelers place on travel time reliability as well as on travelers' values of (average) travel time.[16]

A fifth complication is that congestion affects the magnitudes of other road-traffic externalities including accidents (Hensher, 2006; Steimetz, 2008), emissions (Daniel and Bekka, 2000; Glaister and Graham, 2005) and road damage (Hussain and Parker, 2006). This interdependence would not matter for setting congestion tolls if the external costs of accidents, emissions, and road damage were internalized by efficient pricing or some other means, but since these costs are not fully internalized these knock-on effects should, in principle, be factored in when setting congestion tolls .

A sixth consideration is that externalities and other market failures exist not only in road transportation but also in other transport markets and other sectors of the economy. For example, urban public transit service has scale economies (a positive externality), but it is also heavily subsidized in most cities and fares can be overpriced or underpriced at existing subsidy levels. Labor markets are distorted by income taxes and this has implications for tolling commuting and work-related trips (Parry and Bento, 2001; van Dender, 2003). And traffic congestion affects agglomeration economies in urban areas (Graham, 2007). Levying congestion tolls could exacerbate, or ameliorate, these distortions and studies have shown that the effects may be of first-order importance.

This brief review of the theory of congestion pricing reveals that congestion tolls should be differentiated by vehicle type, road link, time of day, real-time traffic conditions, trip purpose, and local conditions such as pricing of public transit service and other substitute modes of transport. In practice, tolls cannot be freely varied along all these dimensions. For technological, economic, or public acceptability reasons it may not be possible to toll all roads, to adjust tolls frequently by time of day, or to vary tolls according to traffic conditions. Lack of information or

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[15] Nonrecurring traffic congestion accounts for a large fraction of total delays in major urban areas. According to Schrank and Lomax (2009, Exhibit A-9) incident-related delays on US freeways ranged from 70% to 250% of recurring delay in the 43 largest urban areas.

[16] Small and Verhoef (2007, Section 2.6) review the theory and estimation of the value of travel time reliability.

legal prohibitions may also preclude toll discrimination according to certain vehicle or driver characteristics.

In principle, the complications listed above (and many others) should be weighed when choosing a congestion pricing scheme and the levels and structure of tolls. In practice this is infeasible at anything like the theoretical ideal. Nevertheless, if the various complications are simply disregarded a congestion pricing scheme may perform badly, and quite possibly could be worse than doing nothing. Care should therefore be taken in deciding which complications are too important to ignore in a given application.

Congestion pricing schemes can be categorized along several dimensions: (1) the type of scheme (e.g., facility-based, area-based, or distance-based, (2) the degree to which tolls vary over time, (3) other dimensions of toll differentiation, and (4) technology. Section 3 addresses the first three dimensions and Section 4 follows by discussing technology. This sequence is followed for two reasons. First, it facilitates presentation. Second, technology choice is subordinate to choices along the other three dimensions in the sense that technology is not an end itself and should be driven by policy needs. This does not imply, of course, that technology is unimportant. Technology choice affects system infrastructure and operating costs, flexibility, scalability, ability to differentiate tolls and other features of schemes as will be discussed in Section 4. Furthermore, no technology yet exists to implement the most sophisticated forms of congestion pricing that approach the theoretical ideal. Technology choices therefore cannot be made after decisions are made on how to implement congestion pricing. In practice. the choices are likely to be made iteratively and with repeated visits back to the “drawing board”.

3 METHODS OF CONGESTION PRICING

3.1 Types of congestion pricing schemes

Congestion pricing schemes can be classified in various ways. The four categories considered here are presented roughly in order of increasing scale.

Facility-based schemes

For centuries tolls have been imposed on roads, bridges, and tunnels, and this is still the most common form of road pricing by far although congestion pricing per se has only been

implemented on a few facilities. Tolls can be levied either on all lanes of a facility or on designated toll lanes as is done on HOT lane facilities. Tolls can also be levied at a single point on a facility or at multiple points with the total amount paid determined by distance traveled (e.g. as on Highway 407 in Toronto and on the new I-15 Express Lanes which opened in 2009).[17]

Cordons

Toll cordons are a form of area-based charging in which vehicles pay a toll to cross a cordon in the inbound direction, in the outbound direction, or possibly in both directions. A cordon scheme can encompass multiple cordons, and it can include radial screenlines to control orbital movements. All existing schemes are single cordons. The Norwegian toll rings were the first cordons to be created, but their main purpose has been revenue generation rather than congestion pricing.[18] The only cordon scheme designed to manage congestion is the Stockholm congestion charge.[19] The cordon surrounds the city centre and has 18 control points. Tolls are paid on each inbound passage up to a daily maximum of 60 kronors ($8.47). Pricing is in effect on weekdays from 6:30 to 18:30. The toll is 10, 15, or 20 Swedish kronors ($1.41, $2.12, or $2.82) depending on time of day. There is no charge on weekends, holidays, or the day before holidays.[20]

Singapore's Electronic Road Pricing (ERP) scheme, launched in 1998, covers certain expressways and arterial roads as well as three restricted zones in the CBD and the Orchard cordon. It is therefore a hybrid of facility-based tolls and cordons. The charging period is 7:00-10:00 and 12:00-20:00 for the CBD and Orchard cordon, and varies for expressways and

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[17] See http://www.407etr.com/About/tolls.htm and http://fastrak.511sd.com/index.aspx [August 29, 2009].

[18] Toll rings were established in Bergen (1986), Oslo (1990), and Trondheim (1991) as well as Kristiansand, Stavanger, Namsos, and Tønsberg. The Trondheim cordon was converted to a multi-sector zonal scheme in 1996, but tolling ended in 2005 when the policy package that included the toll ring expired.

[19] Since 2002, a £2.00 ($3.26) charge has been levied on vehicles entering the centre of Durham, England. The scheme operates like a cordon although only one, narrow public access road is involved. See Santos (2004) and http://www.durham.gov.uk/Pages/Service.aspx?ServiceId=6370 [August 29, 2009].

[20] For details see Eliasson et al. (2009a).

arterials. Tolls are generally varied every half hour. As in Stockholm, payment is required for each passage or entry.[21]

Zonal schemes

With a zonal scheme (sometimes called an area charge) vehicles pay a fee to enter or exit a zone, or to travel within the zone without crossing its boundary. Zone boundaries can be defined by natural features such as rivers, lakes, oceans, and mountains, as well as by elements of the built environment such as roads, tunnels, bridges, residential neighborhoods, and jurisdictions (states or provinces can define zones). The only operational zonal congestion pricing scheme is the London congestion charge, introduced in 2003. The original charging zone comprised a 21 km^2 area around the city centre. A flat charge of £5 per day was levied on weekdays from 7:00-18:30 for driving anywhere within the zone or for parking on public roads. In 2005, the toll was raised to £8, and in 2007 the charging period was shortened to end at 18:00 and the charging zone was expanded to include residential neighborhoods to the west. Travel along the boundary of the charging zone is free. Several vehicle categories are exempt, and residents of the charge area receive a 90% discount.[22]

Distance-based schemes

With distance-based schemes charges vary with distance travelled, either linearly or nonlinearly. As noted above, some facilities charge on the basis of distance. Networks of truck-only toll lanes and networks of HOT lanes are under consideration[23] and tolls on these networks are likely to be distance-based as well. For schemes that encompass multiple roads or regions the charge rate can depend on type of road. Four US states have implemented distance or weight-based charges for heavy goods vehicles (Conway and Walton, 2009) but the charges are intended to recover the infrastructure costs imposed by heavy vehicles rather than to manage demand. National distance-

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[21] http://www.lta.gov.sg/motoring_matters/motoring_erp.htm [August 29, 2009]. From 1975 to 1998, Singapore operated an Area License Scheme to control traffic in the CBD. Despite its name, the license was only required for vehicles traveling into the charging zone, not within it, and it was therefore effectively a cordon rather than a zonal scheme.

[22] http://www.tfl.gov.uk/roadusers/congestioncharging/ [August 29, 2009].

[23] See Samuel et al. (2002) and Poole and Orski (2003).

based heavy goods vehicle tolls exist in Switzerland, Austria, and Germany, and several other European countries are developing or considering them. For the purpose of this review these schemes are mainly of interest regarding the technologies they use which will be discussed in Section 4.

3.1.1 Degree of time differentiation

Pricing schemes in general — and road tolls in particular — can be characterized as flat, scheduled, or responsive.[24] *Flat tolls* are constant over time. Historically, tolls on most facilities were flat because of technological or administrative difficulties in changing the toll. In some schemes the toll prevails 24 hours a day. In others, such as the London Congestion Charge, the toll is levied at a constant rate during daytime on weekdays and not levied at other times.

Scheduled tolls vary by time of day, day of week, and season according to a predetermined schedule. Examples include some HOT lane facilities in the US, Singapore's Electronic Road Pricing, and Stockholm's congestion charge. The time intervals between toll adjustments varies across schemes, and in some cases the interval in a given scheme varies by time of day.

Responsive tolls vary in real time (or near real time) as a function of prevailing traffic conditions. The only examples of responsive pricing are a few HOT lane facilities where tolls are adjusted to maintain free-flow speeds. During the early 1990s a congestion pricing trial was conducted in Cambridge, UK, in which drivers paid a charge when travel speed dropped below a threshold value. The logic underlying this scheme was similar to responsive pricing on HOT lanes except that the Cambridge scheme applied to all roads within the central city zone.[25]

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[24] Terminology varies. Scheduled pricing is often referred to as "variable", and responsive pricing as "dynamic". Cottingham et al. (2007) use "static pricing" to describe any fixed schedule of charges that is announced well in advance (i.e., before travel decisions are made), and "dynamic charging" to describe charges that depend on contemporaneous congestion. Static pricing in their nomenclature covers both flat and scheduled pricing as defined here, and dynamic charging corresponds to responsive pricing here.

[25] The Cambridge scheme failed to advance beyond the trial because of opposition to the form of pricing and the perception that congestion was not bad enough to warrant tolls. Oldridge (1995) describes the planning, politics, and technology behind the experiment.

Responsive tolls are "reactive" in the sense that they are set (with a short time lag) as a function of current congestion levels. A step beyond reactive pricing in terms of sophistication is an anticipatory, or predictive, scheme in which tolls are based on forecast congestion. Dong et al. (2007) develop an algorithm to implement predictive pricing on a HOT lane facility and show that it can anticipate breakdowns in flow and maintain higher throughput than reactive pricing. Predictive pricing has long been envisaged as a tool for traffic management, but the information, communications, and computational requirements continue to pose a challenge.

3.1.2 Other dimensions of differentiation

As noted in Section 2, optimal congestion pricing calls for tolls to be differentiated in several dimensions in addition to time of day. Differentiation by vehicle type, number of axles, and weight is common practice although these vehicle characteristics are imperfectly correlated with the congestion externality that a vehicle imposes since the externality also depends on road characteristics and the mix of users on the road. Toll differentiation according to speed and other correlates of dangerous driving behaviour has been precluded by lack of information until recently although technological advances in on-board computers now make such differentiation feasible, and possibly practical.

Toll discounts and exemptions for certain categories of vehicles and drivers are quite common. Various categories are exempt from the London and Stockholm congestion charges. London offers a 90% discount to residents, a 12.5% discount to fleets, and various discounts for monthly and annual payments. A number of toll roads and HOT lane facilities also offer quantity discounts in the form of reduced prices for advance purchase of multiple trips, or *ex post* discounts based on cumulative usage over an accounting period. Quantity discounts are commonly used in transportation markets[26] as well as other sectors of the economy, but they are inconsistent with congestion pricing according to marginal social cost pricing principles. In some cases the discounts are used as a way to boost revenues, and in other cases they are offered for public acceptability reasons.

[26] See Anderson and Renault (2009).

3.2 Choice of congestion pricing scheme

Having described the main characteristics of congestion pricing schemes we now turn to the central problem of determining which type of scheme (if any) is best in a given setting. Most studies have focused on the design of a particular type of scheme rather than the choice between schemes although comparisons are becoming more common. Attention is focused here on the choice between facility-based schemes (with varying degrees of road network coverage) and area-based schemes. The most important consideration is whether a scheme can target congestion according to where and when it occurs without inducing excessive spatial or temporal traffic diversion.

As explained in Section 2, link-based congestion tolls are theoretically optimal when all links can be tolled and the tolls can be freely differentiated by link, time of day, vehicle type, and other relevant dimensions. Under these conditions a facility-based congestion pricing scheme with individually-optimized tolls for every facility (link) of the road network would be optimal — at least before tallying toll collection costs. In practice, neither comprehensive tolling nor freely differentiated tolls is likely to be feasible for some time. The degree of network coverage, and the scope for toll differentiation, are therefore key determinants of how well facility-based schemes perform.

High Occupancy Toll lanes are the smallest-scale existing congestion pricing schemes. Tolls are only paid on part of the capacity of a single road and high occupancy vehicles are exempt. Travelers can therefore avoid paying a toll by sharing a ride, by using the toll-free lanes, or by selecting another route if one is available. Simple models with two routes in parallel and identical users (e.g. Verhoef et al., 1996) indicate that the maximum potential benefits from congestion pricing are rather modest unless a large majority of road capacity can be tolled. The economics improve somewhat when heterogeneity of driver preferences is taken into account (Verhoef and Small, 2004) and improve further when value of travel time reliability is factored in (Small et al., 2006). The fraction of the first-best efficiency gains that can be derived from partial network tolling is also higher with scheduled tolls than with flat tolls (Braid, 1996; De Palma et al., 2004) because varying tolls over time to suppress congestion reduces the social cost of trips as well as the amount of traffic diversion onto untolled capacity.

Assessing the performance of partial tolling schemes on real road networks is complicated by the multiplicity of origins and destinations; by differences in the capacities and lengths of links;

and by network topology which creates a complex interdependence between flows — with some links effectively operating as substitutes and others as complements. May et al. (2008) computed optimal (static) congestion tolls on the Edinburgh road network for different numbers of tolled links (n) on the assumption that the set of links that are tolled can be chosen freely for each n. They found that the benefits from tolling increased at a declining rate with n and concluded (p.149) that "less than 10 per cent of the links are required to achieve around 60-70 per cent of the first-best benefits." This conclusion contrasts with the lessons from the two-routes-in-parallel network mentioned above in which there are sharply increasing returns from tolling both routes rather than one. The discrepancy in results highlights the difficulty of drawing general conclusions about the benefits from congestion pricing on networks.

Besides failing to target congestion on part of the network, partial tolling has the drawback that it exacerbates congestion on untolled links and may cause safety and infrastructure damage too if untolled links are build to a lower design standard than the links that are tolled. The extent of traffic diversion depends on the availability of convenient, alternative toll-free links. Re-routing options are limited in some US cities such as Boston, San Francisco, and Seattle, as well as cities such as Stockholm. Traffic diversion has been a problem on some toll roads.[27] Experience varies with the Heavy Goods Vehicle (HGV) charging schemes in Europe. Traffic diversion has been more of a problem in Austria where tolls are imposed only on primary roads, than in Switzerland where tolls are levied on all roads (Sorensen and Taylor, 2005). The German HGV toll is limited to federal motorways and some secondary roads, but traffic diversion has been minimal because many potential alternate routes are either closed to trucks or significantly slower (Broaddus and Gertz, 2008).

Compared to facility-based pricing of individual roads or small-scale road networks, area-based schemes have an advantage in intercepting more trips and are generally less susceptible to traffic diversion.[28] As noted in the introduction, the London and Stockholm schemes appear to be

[27] Swan and Belzer (2008) describe a case of traffic diversion off the Ohio Turnpike.

[28] For example, Olszewski and Xie (2005) find that toll elasticities in Singapore are higher for expressways than for the city centre cordon.

economically beneficial although this has been disputed.[29] Before the Stockholm cordon charge began there was concern that traffic within the zone would increase because no charge is levied while traveling within it. Schemes with sub-zones (as in Trondheim) and differential charge rates were considered before settling on a single cordon with a single charge (Eliasson et al., 2009b).

One reason for the good performance of the Stockholm charge is that the city is built on islands and just 18 access points suffice to form a cordon. In urban areas without natural boundaries choosing the number of cordons and where to locate them can be difficult. May et al. (2008) assess a variety of cordon options for London that differ in the number of cordons, the direction of movement in which charges apply, and the inclusion of radial screen lines. They find that the best-performing option (with three cordons, four screen lines and bi-directional charges) yields several times the benefits from a single cordon. The best single cordon performs poorly because it imposes the same charge on all journeys and allows many journeys to escape payment by rerouting. This illustrates how differences between cities in topology (and perhaps other factors such as population, area, public transit service quality and so on) influence the effectiveness of particular types of schemes.

Zonal schemes share most of the advantages and disadvantages of cordons. Zones are superior insofar as drivers are charged for moving within the zone, although the charge is independent of distance and for very short trips a zero charge would be superior.[30] "The choice between cordons and zonal schemes has not been extensively studied[31] and practical experience

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[29] Prud'homme and Bocarejo (2005) conclude that the London charge is not cost effective, and Prud'homme and Kopp (2006) make a similar claim about the Stockholm charge. Mackie (2005) critiques Prud'homme and Bocarejo's (2005) analysis.

[30] Mayor Bloomberg's initial plan for congestion pricing in New York City featured car tolls of $8 for entering or leaving the charging zone, and a lower $4 toll for driving inside it.

[31] De Palma et al. (2005a) use a dynamic simulator to compare cordon and zonal charges for an area bounded by a ring road on a stylized urban road network. The zonal charge is paid for more trips and has a greater effect on mode choice and departure time decisions. Since average trips within the area are shorter than trips to or from outside, the optimal zonal charge is lower than the cordon toll but it leaves a larger fraction of travelers worse off. Maruyama and Sumalee (2007) use a static network equilibrium

is limited since the London and Stockholm schemes are the only large-scale examples of each type that were designed for congestion pricing.

A frequently asked question is whether area-based schemes of the sort implemented in Europe would work in the US. Several authors in Richardson and Bae (2008) address this question and their overall assessment is negative. Compared to Europe congestion in the US is less concentrated in city centres and more prevalent on expressways. With the exception of New York City no US metropolitan area experiences congestion as severe as London's. Urban sprawl and trip chaining undermine public transit as a viable alternative to driving in the US. Public demands that toll-free routes must exist are also stronger in the US than in Europe, and this too militates against charging whole areas rather than selected facilities.

3.3 Choice of time variation

For each type of charging scheme reviewed in the previous section there is a choice between flat, scheduled, and responsive tolls.

Flat tolls

It is often claimed, or implicitly assumed, that flat tolls are suitable for maximizing revenue whereas scheduled or responsive tolls are preferable to control congestion. Reality is not quite as black and white. A revenue-maximizing toll road operator has an incentive to internalize the congestion costs that users impose on each other and will therefore generally prefer a toll that varies over time. Furthermore, the price elasticity of demand generally varies over time (demand is often less elastic during peak than off-peak periods) and so, therefore, does the profit-maximizing markup that the operator will want to charge on top of the Pigouvian toll. In the case of London travel speeds in the city centre were relatively constant during daytime hours prior to introduction of the charge, and little might have been gained in terms of social welfare by varying tolls during the charge period (Leape, 2006). All that said, given the ease of varying tolls using Electronic Toll Collection technology, either scheduled or responsive tolling is generally preferable for congestion pricing under most circumstances.

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simulation to compare cordon and zonal charges for chained trips in Utsunomiya city near Tokyo. They find that the zonal charge is slightly more inequitable than the cordon toll but the difference in impacts are slight.

Scheduled tolls

Toll schedules are defined by the level set for the toll in each time step and the time interval between steps. Most analytical studies assume that schedules are chosen to be second-best optimal; i.e., to maximize welfare subject to applicable constraints. Practice has been rather more pragmatic. In Singapore, toll schedules are adjusted quarterly, and during June and December school holidays, to maintain target speeds of 45-65 km/h on expressways and 20-30 km/h on arterials at least 85% of the time (Chew, 2008). On SR-91, tolls are adjusted using information on traffic volumes to maintain free-flowing conditions on the Express Lanes without reducing their throughput.[32] Conditions on the general purpose lanes and on other links in the road network are not considered.

The toll setting rules in Singapore and on SR-91 resemble third-best pricing because they apply first-best pricing rules while ignoring congestion levels on untolled links of the network. Third-best pricing is generally inferior to second-best pricing and it can be worse than not tolling at all (Verhoef et al., 1996). However, De Palma et al. (2005b) show that with pure queuing congestion a "no-queue" tolling policy to eliminate queues performs fairly well relative to second-best tolling. Moreover, setting tolls to maintain a target level of service on tolled infrastructure has some advantages.[33] First, it is less computationally demanding than second-best tolling because only information about the tolled links is required. Second, tolls can be found by trial and error and (as in Singapore and on SR-91) periodically adjusted as demand evolves or as capacity changes elsewhere on the road network. Third, the decision rule is readily explained to users and the general public, and fourth it is easy to verify using traffic flow data that the rule is being followed.

The time interval between toll steps varies across schemes. On SR-91 it is one hour, in Stockholm it is 30, 60 or 90 minutes during peak periods and longer during the middle of the day, and in Singapore tolls generally vary every half hour. Schedules with small time steps may be difficult to remember, but they have the advantage that tolls change by small amounts between steps and motorists have less incentive to speed up or slow down in order to catch the

[32] http://www.91expresslanes.com/generalinfo/policyupdates.asp

[33] For further discussion see De Palma et al. (2005).

"lower" toll. In 2003, Singapore introduced five-minute graduated rates between some half hour periods for this reason (Chew, 2008).

Responsive tolls

Responsive tolls have only been implemented to date on a few HOT lanes. On I-15 in San Diego and I-394 in Minneapolis the goal is to maximize utilization of the toll lanes while maintaining free-flow speeds. Tolls are adjusted as frequently as every six minutes on I-15 and every three minutes on I-394. Responsive pricing has the advantage that tolls can be adjusted according to actual travel conditions. Thus, if an accident blocks a lane on a multi-lane highway, the toll can be raised in order to limit the number of drivers who enter the lane during the disruption.

Responsive tolling has worked well on HOT lanes, and it may be practical on individual facilities where all capacity is tolled. But there are several caveats. First, responsive tolling would probably not be suitable for area-based schemes unless public transit and other alternatives to driving have adequate capacity to accommodate travelers who do not want to pay a high toll. Second, responsive tolling can be effective only if travelers are aware of tolls sufficiently far in advance for them to modify their travel decisions. Third, individuals may be risk-averse to uncertain charges (Bonsall and Knockaert, 2008). Indeed, some businesses were against responsive tolling on I-15 because it would create uncertainty about their monthly bills (Bonsall et al., 2007).

3.4 Scheme complexity

The efficiency of markets depends on how much consumers know about prices and how much effort they have to expend to obtain the information. This general economics principle applies to the use of roads and tolls. From a user's perspective the complexity of a congestion pricing scheme depends on how much tolls vary by type of road, location, and time of day; whether tolls are responsive; how total amount paid varies with distance driven, and so on. Are there discounts for purchasing multiple cordon passes? Are there ceilings on the amount paid per day? Does the charge paid depend on the method of payment?

The dangers of designing an overly complex price system are highlighted in the recent report of the US National Surface Transportation Infrastructure Financing Commission (2009, p.141):

> "Even a road pricing system … where the payment system does not change, entails new information about the costs of traveling at certain times and on certain roads. This requires people to know more and to make more informed and more frequent decisions about travel."

If travelers are misinformed about tolls they are liable to make mistakes that leave them worse off and that also undermine overall system efficiency because their responses deviate from what is intended. As travelers become accustomed to a charging system they may err less frequently, but they may also fall into habits and fail to modify their decisions if circumstances change. And if the system is very complex it may be strongly opposed. As Bonsall et al. (2007, 680) remark: "A prime requirement is that the logic of the charge structure, and the necessity of a degree of complexity, is capable of being communicated and is seen to reflect the objectives of the scheme."

4 CONGESTION PRICING TECHNOLOGIES

4.1 Functions to perform and types of systems

All congestion pricing technologies must perform three basic functions: (1) measurement of road usage by identifying vehicles and recording their locations and/or the distance they have traveled, (2) communication of data for billing purposes, and (3) enforcement. With conventional systems that use toll booths vehicle detection and payment are done manually and access is controlled by physical barriers. Toll booths have largely given way to Electronic Toll Collection (ETC) technology which allows drivers to pay without using cash or stopping. There are three types of ETC systems (Noordegraaf et al., 2009):

1. Roadside-only systems that use Automatic Number Plate Recognition.
2. Tag & beacon systems that use short-range microwave technology: either Dedicated Short Range Communications, or infrared-based.
3. In vehicle-only systems that rely either on satellites or cellular networks.

Roadside-only systems and tag & beacon systems require roadside infrastructure and only record point data. To determine distance traveled a vehicle must be detected at a sequence of locations. (Distances can also be measured directly using odometers and (in the case of trucks) electronic tachographs.) In vehicle-only systems track a vehicle's course and do not require roadside

infrastructure although infrastructure-based technology may be used in tandem for enforcement purposes.

4.2 Component technologies

Each of the three types of ETC system comprises one or more component technologies that each perform one or more of the three basic functions (Table 1).

4.2.1 Automatic Number Plate Recognition

Automatic Number Plate Recognition (ANPR) technology uses digital cameras and optical character recognition (OCR) software to record an image of a vehicle and its license plate. ANPR is used standalone with roadside-only systems although this requires collecting and processing images for every vehicle. ANPR is more commonly used for enforcement because only violators have to be processed and — unlike other technologies — ANPR does not require that vehicles have equipment in working condition.

4.2.2 Dedicated Short Range Communications

Dedicated Short Range Communications (DSRC) is a means of Automated Vehicle Identification (AVI). Antennas mounted on overhead gantries communicate with tags or transponders on vehicles as they pass by. Like ANPR, DSRC technology can be used for all three basic functions: road usage measurement, data communication, and enforcement. DSRC is used on many existing facility-based road pricing schemes. It can also be used in conjunction with on-board units (see vehicle equipment below) to operate a zonal tolling system by activating a vehicle's on-board unit when it crosses into the zone, and deactivating it when the vehicle leaves the zone.

4.2.3 Satellite systems

Global Positioning System (GPS) technology, developed by the US military, is a member of a class of systems called Global Navigation Satellite Systems (GNSS) which include the European Galileo system that is under development. GPS is used for navigation and other military and civilian functions. GPS can be used in conjunction with General Packet Radio Service (GPRS): a cellular data service for communications, and with Geographical Information Systems (GIS) that

translate latitude and longitude data into locations on a digitized road map. A drawback of GPS is that satellite signals can be lost in tunnels, and intercepted by overpasses and high buildings (the urban canyon effect). For backup, odometers can be used to record distance and dead-reckoning can be used to keep track of location (although accuracy declines with distance traveled).

4.2.4 Cellular networks

Cellular networks are used by cellular phones. The most popular standard is Global System for Mobile (GSM) communications which uses Short Message Service (SMS). Cellular networks show promise as a means of for road pricing although the application is not as well developed as it is for GPS. Like GPS, cellular networks do not require roadside infrastructure and communications is possible anywhere rather than being restricted to gantries or locations where transponders have been installed.

4.2.5 Vehicle equipment

All vehicles are equipped with a Vehicle Identification Number (VIN) that conveys such information as vehicle class, year of manufacture, make, model and weight. On-board units are more elaborate devices with computational capabilities, memory storage, and an interface for communication with DSRC, GPS, or cellular networks. Transponders are used for communication using DSRC.

4.3 Technologies used in existing road pricing schemes

This section provides an overview of a sample of road pricing schemes to illustrate the range of technologies and technology combinations that are either being used for congestion pricing or can be adapted to implement it. The list in Table 2 covers four categories: HOT lanes, area-based schemes, European distance-based heavy goods vehicle schemes, and US studies of distance-based charges for passenger vehicles.

High Occupancy Toll (HOT) lanes

SR-91 in Orange County, California was the first HOT lane facility in the world. Tolls are scheduled.[34] I-15 in San Diego was the second facility and the first to adopt responsive tolls; it is currently being expanded to a managed lanes facility with multiple entry and exit points and tolls that are based on distance traveled. I-394 was the second facility to adopt responsive pricing and the first to separate toll lanes from general-purpose lanes using only striping rather than barriers.[35] All three facilities use transponders for road use measurement and communications, and all three rely on visual inspection to enforce occupancy requirements (as do all other High Occupancy Vehicle (HOV) and HOT facilities). The three facilities differ in the vehicle occupancy requirement for toll exemptions or discounts and in the range of technologies used to verify payment and to intercept violators.

Area-based schemes

The Singapore, London, and Stockholm schemes are the only area-based schemes designed to control congestion. Singapore's ERP scheme uses DSRC technology for road use measurement whereas London and Stockholm use ANPR.[36] Ken Livingstone was determined to implement a congestion charge during his first term as mayor of London and he opted for ANPR as a proven and low risk technology despite its high infrastructure and operating costs. During the Stockholm trial in 2006 both ANPR and transponders were used and approximately half the transactions were processed by each mode. ANPR worked so well that transponders were abandoned when the scheme became permanent in 2007. Transponders are still used for vehicles that are exempt from payment.

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[34] Dynamic pricing of SR-91 is being studied as a Value Pricing project **(**FHWA, 2008).

[35] Several other HOT lane facilities are operating and a number of new ones are either being built or planned. Some will feature scheduled tolls, and others responsive tolls; see FHWA (2008).

[36] Both ANPR and transponders were used during the Stockholm trial in 2006, and approximately half the transactions were processed by each mode. ANPR worked so well that transponders were abandoned when the scheme became permanent in 2007. Transponders are still used for vehicles that are exempt from payment.

4.3.1 European distance-based Heavy Goods Vehicle schemes

In Switzerland, Austria, and Germany, heavy goods vehicles (HGVs) pay tolls proportional to distance traveled on some, or all, roads. None of the three scheme was designed for congestion pricing although the Austrian and German technologies permit some differentiation of tolls by time and location.

The Swiss toll applies to HGVs over 3.5 metric tons gross vehicle weight and is paid on the whole 71,000 km national road network. It is differentiated by emissions class[37] but not by type of road or time of day. Distance is recorded using a digital tachograph and a smart card. The unit is activated by roadside DSRC transponders when a vehicle enters the country and deactivated when it exits. Charges are paid by inserting the smart card into a roadside terminal (Cottingham et al., 2007).

In contrast to the Swiss system, HGV tolls in Austria are only charged on the 2,060 km primary road network and are not differentiated by emissions class. An on-board unit called a "Go Box" is used for communications. The Swiss on-board unit can be used in Austria.[38]

The German HGV scheme applies to federal motorways and some secondary roads (12,000 km in total). Toll differentiation is similar to Switzerland but the technology is more advanced in using GPS to measure distance and GSM for communications. DSRC beacons are used for backup location information (Cottingham et al., 2007). The system is scalable in that more roads can be added, and the technology allows tolls to be differentiated by road type and time of day.

Belgium, the Czech republic, Denmark, France, Hungary, Slovenia, Slowakia and Sweden are all considering HGV charging schemes that vary according to class of road covered, scope of toll differentiation, and technology (GINA, 2009; Noordegraaf et al., 2009; Dutch Ministry, 2009). The UK Department for Transport (2004) proposed a national scheme of road pricing for Great Britain with HGVs to be charged first. Tolls were to be differentiated by type of road, vehicle weight, number of axles, and emissions class, followed later by possible further differentiation by time of day and geographic area (Sorenson and Taylor, 2005). However,

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[37] The toll rate is set to reflect the costs of health care, accidents, damage to buildings, and noise (Broaddus and Gertz, 2008).

[38] Most existing tolling schemes are not interoperable either between countries or within them.

projected costs for the technology escalated, and the plan was eventually abandoned — ostensibly on the grounds that it should be integrated with charging of passenger vehicles.

4.3.2 Plans for distance-based charges for passenger vehicles

Several countries have studied distance-based charges for passenger vehicles. As just noted, a scheme was planned for Great Britain but it has been shelved in the face of strong public opposition. In 2008, the Dutch Parliament approved a national distance-based system of user charges (the Dutch Mobility Plan) that uses satellite technology and is to be introduced from 2012 to 2017. The fee per kilometer will be differentiated by emissions class and time of day.

The US is in the preliminary stages of considering a Vehicle Miles Traveled (VMT) fee as a long-run alternative to fuel taxes as the primary funding mechanism for roads. Depending on the technology used the fee could be varied by time, distance, and location to price congestion. Several US experiments with regional distance-based pricing have been conducted or are under way that provide evidence on the technological possibilities and challenges (see Table 2). The Oregon Vehicle Miles Traveled Pricing Pilot Project (2004-2006) was designed to test the viability of distance-based charges as a replacement for fuel taxes.[39] Charges were defined by zone and set higher during AM and PM peak periods. Test vehicles were equipped with GPS devices that recorded mileage but only aggregate distance was recorded and vehicle movements could not be tracked.. The distance-based charge was paid automatically when the vehicle refueled at participating gasoline stations and the state fuel tax was deducted from the bill. The study found that GPS technology was reliable and assured privacy protection.

The Puget Sound Regional Council conducted a six-year study (2002-2008) of driver responses to network-wide facility-based tolls.[40] Tolls were differentiated by road type (higher on freeways than on arterials) and time of day (substantially higher during AM and PM peaks).[41] Unlike in the Oregon project GIS was required in combination with GPS to record separately

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[39] See Whitty (2007, 2009).

[40] See Puget Sound Regional Council (2002), Whitty (2009) and www.psrc.org/projects/trafficchoices.

[41] The tolls were virtual in the sense that test volunteers did not actually incur out-of-pocket costs.

distances traveled on freeways and arterials. Test results were used to assess the merits of several road pricing schemes ranging from HOT lanes to all freeways and major arterials.

A third study, launched in 2005 and administered by the University of Iowa, is conducting a feasibility assessment of GPS-based tolling technology as well as gauging drivers' responses and public attitudes towards it.[42] Several test sites are located across the country. As in the Puget Sound study GIS is used in combination with GPS to record distances within the region, to compute charges on the vehicle, and to download updates to the database. Only aggregate charging data is transmitted from the vehicle. Unlike in the Oregon and Puget Sound studies, tolls are flat.

4.4 Choice of technology

Any congestion pricing technology (or road pricing technology in general) has to perform the three basic functions of road use measurement, communication of billing data, and enforcement. The best technology choice depends, *inter alia*, on the type of charging scheme and the degree of toll differentiation to be implemented. Assessments are made here for the four technology systems evaluated by Noordegraaf et al. (2009), referred to here as *ANPR*, *DSRC*, *Satellite*, and *Cellular*. Table 3 reproduces Table 2 in Noordegraaf et al. (2009) with the exception of omitting the privacy criterion which is discussed subsequently as well as several additional assessment criteria. Noordegraaf et al. rank the systems for applications to distance-based charging All the criteria are relevant for tolling facilities, cordons, and zones as well although the rankings vary.

4.4.1 Location accuracy

Location accuracy refers to accuracy in detecting and identifying vehicles and recording where they are. *ANPR* and *DSRC* use infrastructure in the vicinity of roadways and can identify location precisely if they receive a proper signal. Modern *DSRC* technology has a recognition accuracy of 99% or better. *ANPR* has several limitations. It can fail in bad weather or when the camera view of a number plate is obscured by dirt or other vehicles. Readability of license plates varies by country. And on multilane highways cameras must be mounted overhead on gantries rather than beside the roadway to provide adequate lines of sight.

[42] See www.roaduserstudy.org and Kuhl (2009).

Satellite systems provide nearly ubiquitous coverage. But their resolution is inferior to infrastructure-based technology and they can fail to distinguish between closely-spaced roads.[43] As noted earlier, GPS signals can be disrupted by the urban canyon effect which is a greater problem in cities where accuracy is most important.[44] Another limitation is that commercial GIS maps do not always provide a consistent level of accuracy (Donath et al., 2009). Unlike GPS, *cellular* systems are not susceptible to the urban canyon effect. But their spatial resolution is limited by cellular tower density, which makes them more suitable for zonal than facility-based schemes (although density tends to be higher in cities).

4.4.2 Roadside infrastructure costs

ANPR and *DSRC* require roadside infrastructure whereas *Satellite* and *Cellular* do not unless *ANPR* and *DSRC* is used for enforcement. Roadside infrastructure is expensive to install, occupies space, is costly or impossible to relocate, requires maintenance, and is susceptible to vandalism. Given the high costs, *ANPR* and *DSRC* are likely to be economic only for tolling heavily used facilities. Collection costs for legacy facility-based systems in the US amount to roughly 16% of toll revenues (NSTIFC, 2009). For cordon and zonal schemes the corresponding percentages are somewhat higher: 21% in Singapore, 22% for the Stockholm Trial, and 50-60% for London.[45] In contrast, operating costs are lower for the HGV schemes in Europe: 4% for Switzerland, 9% for Austria, and 16% for Germany (Broaddus and Gertz, 2008)[46]. These lower percentages are attributable in part to the relatively high per kilometer fees that trucks pay and the long distances they travel.

The costs of national schemes that cover all vehicles are difficult to estimate — especially since the costs are sensitive to details of the technology choice (Glaister and Graham, 2008). The

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[43] The European Union is developing another GNSS system, Galileo, which will be more accurate than GPS. However, Galileo is several years behind schedule (http://www.insidegnss.com/node/1426#Baseband_Technologies_Inc [July 24, 2009]).

[44] Samuel (2009).

[45] These figures are reported, along with sources, in Lindsey (2007, Table A1).

[46] Capital costs are 4% of revenues for Switzerland, 3% for Austria, and 7% for Germany (Broaddus and Gertz, 2008).

Dutch government has set a goal to limit administrative costs to 5% of revenues. Since much of the costs of *Satellite* and *Cellular* systems are fixed, average total costs are likely to be lower for large countries. A further consideration in choosing a congestion pricing technology is that a system may be capable of providing additional services such as pricing of parking and insurance, navigation assistance, revenue generation, and so on. If so, the full system costs are not wholly attributable to the congestion pricing function. The attributable portion depends, *inter alia*, on which service is considered incremental which may not be clear.

4.4.3 In-vehicle equipment costs

Except for readable license plates *ANPR* does not need vehicle equipment whereas the other three technologies require on-board units. *DSRC* systems require a transponder. *Satellite* systems require an antenna, a power source, and (for systems that use GIS) digital maps with sufficient accuracy to locate a vehicle on a particular road (Donath et al., 2009). Mobile phones can be used as OBUs with *Cellular* systems, and this reduces the costs since most drivers already have a mobile phone although phones must somehow be linked to a given vehicle (Cottingham et al., 2007).

4.4.4 Flexibility

System flexibility has several dimensions: flexibility to redeploy or expand the charging area, flexibility to modify or extend toll differentiation by road, time of day and vehicle characteristics, and flexibility to add services such as route guidance. Infrastructure-based systems tend to be less flexible than in-vehicle systems in all three respects. Since *ANPR* does not use in-vehicle equipment *ANPR* systems cannot be changed or improved using vehicle technology. And *DSRC* systems are less flexible than *Satellite* and *Cellular* systems because they tend to use OBUs with fewer capabilities (Noordegraaf et al., 2009).[47]

[47] In the University of Iowa experiment toll tables can be updated by downloading new tables over cellular networks (Kuhl, 2009).

4.4.5 Scalability

The scalability of a technology is inversely related to the amount of roadside infrastructure it requires. *ANPR* and *DSRC* are therefore at a marked disadvantage relative to *Satellite* and *Cellular* for regional, intercity, or national applications. Indeed, the London congestion charge could not economically be expanded to include Greater London even if the charging area remained as a single zone (Cottingham et al., 2007). *Cellular* systems based on text messaging have an advantage over other cellular technologies since they require less bandwidth and can be implemented using most cellular networks (Donath et al., 2009).

4.4.6 Privacy protection

Privacy protection has been a challenge for electronic road pricing at least since Hong Kong's electronic road pricing experiments in the 1980s. Noordegraaf et al. (2009) argue that legislation is sufficient to ensure privacy protection. This is debatable given the various, ingenious ways that scofflaws find to bypass technological safeguards, and the danger that governments may circumvent or override laws — whether in the pursuit of criminal activity or for other reasons. Privacy concerns could be assuaged by not keeping records of vehicle movements but this would undermine system accountability. The use of *ANPR* in London and Stockholm for road use measurement has not evoked adverse reactions and *ANPR* is used for enforcement in many other systems. *Satellite* and *Cellular* systems are more vulnerable to interception than *ANPR* or *DSRC* because information is transmitted over much longer distances. This problem can be alleviated by performing calculations with on-board units and limiting communications to aggregate amounts owed. A further concern is that systems with on-board units that record travel speed could provide information that is used in court in case of an accident or by insurance companies to adjust insurance rates (Sorensen and Taylor, 2005).

4.4.7 Enforcement

Enforcement is required to intercept vehicles without functioning in-vehicle equipment, or equipment that has been corrupted to provide false identification or other information. Of the four technologies, only *ANPR* does not rely on in-vehicle equipment and — except for problems with false or stolen number plates (as has occurred in London) — *ANPR* is robust to tampering. *ANPR* is the most common means of enforcement for facility-based and area-based congestion

pricing schemes (cf. Table 2). Its big drawback for regional, intercity, or national applications is the high cost of establishing cameras throughout the network although, as Cottingham et al. (2007) point out, it may be possible to achieve sufficiently high rates of detection for deterrence purposes if cameras are limited to intersections and high-volume links.

An alternative to cameras or other fixed infrastructure enforcement technologies are mobile monitors or readers such as those used by the German HGV system and on I-394. Mobile enforcement is more cost-effective relative to stationary enforcement methods when only certain categories of vehicles (e.g. trucks) are tolled.

An additional enforcement task in the case of HOT lanes is to verify that vehicles choosing not to pay a toll meet the minimum vehicle occupancy requirement. Visual inspection has proved to be unreliable and it is also costly in labour input as well as land at facilities where an extra lane is built as an "enforcement zone" to facilitate observation. Research is underway on automated vehicle occupancy verification technologies that operate either on the roadside or inside vehicles. According to Poole (2009) most of the roadside systems cannot yet detect people in rear seats (which is required to enforce HOV3+ requirements) and in-vehicle system face legal challenges due to privacy concerns.[48]

4.4.8 Scope for toll differentiation

Toll differentiation by vehicle characteristics such as number of axles, GVW, and emissions class can be done using any of the technologies simply by registering the vehicle on a database (Noordegraaf et al. (2009). Differentiation by time of day is also straightforward. Differentiation by road type is done automatically with facility-based schemes. For distance-based schemes DSRC is used with the Austrian HGV charge, while GPS is used in Germany and in the Puget Sound study.

Discounts and exemptions are provided to several categories of users in the London and Stockholm schemes by either registering them in a database or using DSRC (in Stockholm). Exemptions may also be desired for certain users on private roads and for residents on local public roads who have paid for roads with property taxes. Such exemptions can be implemented

[48] As an alternative to a technology solution Poole suggests that policy be changed to require all vehicles using HOT lanes to carry a transponder and to require vehicles used for toll-free carpooling to pre-register

by locating transponders or beacons at appropriate points on the network. Since satellite technology allows vehicles to be tracked it may be possible to price discriminate according to where vehicles are coming from and where they are going. For example, tolls could be set as an increasing function of the fraction of users coming from outside the jurisdiction responsible for tolling (Roth, 2009). Tolls could also be differentiated vehicle-by-vehicle although this may be illegal.

4.4.9 Additional services

The four technologies differ widely in their scope for providing services besides toll collection. For *ANPR* there is no scope other than using vehicle and license plate images for law enforcement. *DSRC* is also limited by the capabilities of on-board units and by the fact that communications is possible only when vehicles are near receivers. *Satellite* and *Cellular* systems offer greater potential for providing navigational aid and travel advisories, as well as charging for parking, insurance and other services. Grush and Roth (2008) describe a system — similar to that used for telecommunications — that would perform these functions with charges differentiated by time, distance, and place.

4.5 Traveler information[49]

Information about travel conditions helps individuals make optimal mode, departure time, route and other travel choice decisions.[50] For decades, travel information has been available from traditional sources such as newspaper, television, commercial radio and Highway Advisory Radio, as well as field devices such as changeable message signs. Television can provide relatively up-to-date information, but neither television nor newspapers provides en-route information. Message signs have the advantage of providing relevant location information

[49] This section draws heavily on NCHRP (2009).

[50] System operators also require information to set optimal congestion tolls — whether this be information on average annual daily traffic flows to set flat tolls, or real-time information on weather and incidents to set responsive tolls. Information can be obtained from many sources including conventional traffic counters, loop detectors, wireless radar, helicopter patrols, updates from road construction and maintenance departments, and reports from motorists.

without requiring drivers to do more than look at the signs. But signs are limited in how much information they can convey, and they cannot provide pre-trip travel information. Signs are also costly to install and maintain.

Starting in the 1990s new information sources have become available: traffic websites, cellular phones, smart phones, Personal Intelligent Travel Assistants, and (in the US) publicly-operated 511 phone systems. In addition to navigational assistance and other services these technologies can provide travelers with information about tolls. In the case of flat or scheduled tolls, rates can be posted on the internet and viewed or downloaded at home. Conveying responsive tolls is more challenging because tolls can change rapidly and pre-trip information may be obsolete by the time the toll is paid. Portable devices or in-vehicle screens that display real-time tolls may be useful (Cottingham et al., 2007; Noordegraaf et al., 2009). Nevertheless, making complex trip decisions en-route, or even pre-trip, may be so cognitively demanding that travelers will prefer to delegate decisions to on-board units on their vehicles, or to central computers of the information service provider or toll operator. Travelers could program an on-board unit to select a route with the shortest distance, shortest expected travel time, or lowest expected generalized cost. Websites already exist that do this. For example, Traffic.com allows users to specify a starting point and ending point.[51] Using real-time information derived from proprietary and external sources it determines two routes: a direct route and a route with the shortest current travel time. Information is provided for each route on distance, drive time, speed limit, delay, and average speed. A "jam factor" (on a scale of 0-10) is also reported for major roads along the routes as well as the number of incidents in progress and an indication whether congestion is "building", "holding", or "clearing". Motorists can receive traffic alerts by SMS, automated voice call, and e-mail. The service is provided free in 52 US cities.

5 CONCLUDING REMARKS

Congestion pricing is an idea with a long academic pedigree that is slowly gaining credence amongst practitioners and policymakers. The rate at which congestion pricing is implemented, and its ultimate scope, will depend on what technology is used and on what other functions and services can be performed with the technology. Since congestion pricing calls for the greatest

[51] http://www.traffic.com [September 4, 2009].

overall degree of toll differentiation according to vehicle characteristics, location, time of day and real-time conditions, congestion pricing is likely to drive the technology choice. The economics of congestion pricing are much more attractive if the cost of congestion pricing is considered incremental to the cost of a system that can perform other functions than if the whole cost is attributed to congestion pricing alone.

The scope of a congestion pricing scheme is defined by how much of the road network is covered, what vehicles pay tolls, and the degree to which tolls are differentiated. Most studies argue that congestion pricing should be implemented in steps rather than as a "big bang" (Verhoef et al., 2007). Staged implementation may be necessary to overcome public opposition to congestion pricing by demonstrating its benefits without committing huge amounts of resources or exposing large numbers of unwilling participants to potentially significant losses. Limited-scale experiments are also useful for testing new technologies and determining which technology works best for a given type of congestion pricing scheme in a given area.

Congestion pricing is a limited patchwork of schemes at present. Facility-based schemes dominate in North America. Europe has a few area-based urban congestion pricing schemes and a few intercity distance-based schemes for heavy goods vehicles that are designed primarily for revenue generation and internalization of external costs other than congestion. Since congestion is concentrated in cities this emphasis of the European HGV schemes is understandable. However, the technologies used for distance-based pricing can be adapted to congestion pricing. Furthermore, governments are facing growing pressure to generate more revenues from user-based charges, and to transition away from fuel taxes. Distance-based charges can be used for this purpose and they can be applied to passenger vehicles as well as freight vehicles.

There are several reasons to implement distance-based tolls for heavy goods vehicles first. Many HGVs are already equipped with GPS-based fleet management systems and additional equipment for levying tolls can be added at moderate cost. Toll collection costs per unit of revenue are likely to be much lower than for passenger vehicles because trucks are driven long distances and pay higher tolls per kilometer. And truck drivers and shippers are already familiar with the technology and seem less concerned about privacy than automobile drivers. Some new automobiles are equipped with on-board units that make distance-based pricing practical at

reasonable cost.[52] However, older vehicles lack this equipment and retrofitting is difficult and costly (Whitty, 2009). A prolonged phase-in period for passenger vehicles is therefore likely before satellite (or possibly cellular) technology could become universal.

Universal coverage of the road network is also unlikely to be achieved for some time — in part because toll enforcement is not yet possible without some form of roadside infrastructure that is expensive to build and operate on a wide geographical scale. Traffic diversion from tolled to untolled roads is therefore a potential problem, and the challenges of second-best pricing discussed in Sections 2 and 3 will remain relevant.

The history of successes and failures with road pricing suggests that simple systems that can be expanded and upgraded stand a better chance of successful implementation than systems that try to achieve theoretical perfection. Hong Kong and Cambridge experimented with sophisticated technologies and their complexity contributed to the failure of the plans to advance beyond the trial stage (Ison and Rye, 2005). Problems with the complex technology of the German HGV charge also forced the initial roll out to be aborted. Part of the problem was incompatibilities of the component technologies. As Noordegraaf et al. (2009) note, technologies can interact in unforeseen ways and assembling component technologies that have been proven in isolation may not result in a working overall system.

A further lesson is that congestion pricing schemes cannot be planned once-and-for-all and then left alone, but need to evolve and be fine-tuned. The Singapore, London, and Stockholm schemes demonstrate this well. Singapore launched its Area Licensing Scheme in 1975 with a daily entry fee into the restricted zone that applied only in the morning.[53] An evening charge was added in 1988. In 1994, separate permits were issued for all-day entries and entries restricted to the middle of the day. Paper-based licenses were replaced by electronic road pricing in 1998. Graduated rates to smooth the toll changes between half-hour periods were introduced in 2003.

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[52] For example, since 1996 vehicles sold in the US are equipped with a data bus called an on-Board Data link 2 that — in conjunction with an on-board unit — can be used to compute distance and communicate with a back office via SMS text messaging (Donath et al., 2009).

[53] The history of road pricing in Singapore is described in Gómez-Ibáñez and Small (1998), Santos et al. (2004), Christainsen (2006), and Chew (2008).

A gantry that operates only in the evening to toll outbound trips was set up in 2005. And, as discussed earlier, toll rates are adjusted quarterly to maintain target speeds.

The main changes to the London scheme have been an increase of the charge from £5 to £8 in 2005, and the Western Extension of the charging zone in 2007. Ken Livingstone, the former mayor, proposed to differentiate the charge by vehicle emissions but this was not implemented. The new mayor, Boris Johnson, plans to abolish the Western Extension. Travel speeds have been decreasing since 2005 (Transport for London, 2008). This is attributed to reallocation of road space away from cars to buses, taxis and bicyclists (Santos, 2008), and may prompt an increase in the toll or a reduction in discounts and exemptions.

Despite its relatively short history the Stockholm charge has evolved too. As noted earlier, both transponders and ANPR were used for the trial but transponders were discontinued when the charge was made permanent. Exemptions for taxis were also eliminated. As in London, travel speeds have been falling. Hultkrantz and Liu (2009) provide evidence that the deterioration is due to a combination of rapid growth in the share of "green" cars that are exempt from the charge, a decision to make charges deductible from income tax, and reductions in the real value of toll rates.

These developments point not only to the need for continuing appraisal of scheme design, but also the importance of taking into consideration other policies that may be implemented — either in combination with congestion pricing as part of a policy package, or independently. Congestion pricing schemes should be developed and implemented with a view to their broad implications and consistency with other policies.

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9 TABLES

Table 1 : Congestion pricing functions and technologies

Technology	Road use measurement	Data communication	Enforcement
Odometer/tachograph	Distance		
Dead reckoning	Distance		
OCR/ANPR	Location	Bills sent to user by post, deducted from bank account, etc.	√
DSRC	Location	√	√
GNSS (e.g. GPS)	Location	with GPRS	
Cellular networks	Location	with GPRS	
Smart cards		√	
Enforcement beacons			√
Enforcement transponders			√
Mobile monitors with readers			√

Notes: **ANPR** = Automatic Number Plate Recognition; **DSRC** = Dedicated Short Range Communications; **GNSS** = Global Navigation Satellite Systems; **GPRS =** General Packet Radio Service**; GPS** = Global Positioning System; **OCR** = Optical Character Recognition.

Sources: Various

Table 2: Selected congestion pricing schemes and technologies

	Coverage and toll differentiation	Road use measurement	Communications	Enforcement
HOT lanes				
SR-91/Orange County (1995)	Scheduled. HOV3+ exempt except eastbound on weekdays 4 pm -6 pm	FasTrak transponder	Transponder. Prepaid account	Cameras, enforcement beacons
I-394 (2005)	Responsive. HOV2+ exempt	MnPass transponder	Transponder. Prepaid account	Enforcement transponders, mobile readers
I-15 Managed lanes/San Diego (2009)	Responsive. Distance-based. HOV2+ exempt	FasTrak transponder	Transponder. Prepaid account	FasTrak smartcard identifies violators
Area-based schemes				
Singapore (1998)	Expressways & arterials + CBD + 1 cordon. Scheduled. By road and vehicle type	DSRC	DSRC and IVUs with smartcard	ANPR
London (2003)	Charging zone. Flat. Various exemptions	ANPR	Manual by various means	ANPR
Stockholm (2007)	Cordon. Scheduled. Various exemptions	ANPR. (Transponders for exempt vehicles.)	Monthly bill with payment by various means	ANPR
European distance-based heavy goods vehicle schemes				
Switzerland (2001)	All roads. Flat. By no. axles, emissions class, GVW > 3.5 tons	Tachograph and smartcard	DSRC and smartcard	ANPR & DSRC with GPS backup
Austria (2004)	Primary roads. Flat. By no. axles. GVW > 3.5 tons	DSRC	OBUs “Go Box”	Cameras
Germany (2005)	Federal motorways &	GPS	GSM	Mobile monitors DSRC backup

	some secondary roads. Flat. By no. axles, emissions class. GVW > 12 tons			
US studies of distance-based charges for passenger vehicles				
Oregon (2004-2006)	Zonal. Scheduled	GPS & odometer (no GIS)	DSRC at gasoline stations	N/A
Puget Sound Regional Council (2002-2008)	Freeways & major arterials. Scheduled. By road type	GPS with OBU equipped with GIS	Cellular	N/A
Iowa (2005-2010)	Regional. Flat. By vehicle class, & road type eventually	GPS with OBU equipped with GIS	Cellular	Odometer & dead reckoning backup. GPS validation

Notes: **ANPR** = Automatic Number Plate Recognition; **DSRC** = Dedicated Short Range Communications; **GIS** = Geographical Information System; **GPS** = Global Positioning System; **GSM** = Global System for Mobile communications; **GVW** = Gross Vehicle Weight; **HOV** = High Occupancy Vehicle; **IVU** = In Vehicle Unit; **OBU** = On Board Unit.

Sources: Cottingham et al. (2007), Nash et al. (2008), GINA (2009), Noordegraaf et al. (2009)

Table 3: Technology comparisons for distance-based charging

	ANPR	*DSRC*	*Satellite*	*Cellular*
System type	Roadside-only	Tag & beacon	In-vehicle only	In-vehicle only
Road use measurement	ANPR	On Board Unit	GNSS	Cellular network
Data communication		DSRC	GPRS	GPRS
		Assessment criteria		
Location accuracy	+	+ +	+ +	+
Roadside infrastructure costs	- -	- -	+ +	+ +
Vehicle equipment costs	+ +	-	-	-
Flexibility	- -	+	++	++
Scalability	- -	- -	+ +	+ +

Notes: **ANPR** = Automatic Number Plate Recognition; **DSRC** = Dedicated Short Range Communications; **GNSS** = Global Navigation Satellite Systems; **GPRS =** General Packet Radio Service

Source: Noordegraaf et al. (2009, Table 2)