Examining the Linkages between Electronic Roadway Tolling Technologies and Road Pricing Policy Objectives

Submitted for presentation at the

World Conference on Transportation Research

and submitted for publication in the

Transport Policy

September 2010

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Abstract

The surge of road pricing projects in the U.S. and around the globe over the past 15 years has been enabled by a variety of new communication and transportation technologies. While all of these technologies increase the efficiency of roadway tolling vis-à-vis manual collection, no "best" configuration has emerged. Rather, optimal configurations depend on the objectives of the tolling effort, such as facility type, geographic scope, desire to price externalities, integration with other operations, and so on. While such policy objectives for road pricing have been examined extensively, little has been written on the explicit links between tolling technology configurations and policy objectives. This paper addresses this gap in the literature through an examination of eight road pricing programs. For each program we evaluate the conduct of the three technical tasks via the nine technology sets in light of six principal policy objectives of road pricing.

We find that two policy factors most often determine the type of roadway tolling technologies adopted: (1) the geographical scale of the road network tolled, and (2) the complexity of calculating the fee to be charged. The combination of these two factors can vary greatly – from flat fare tolling on individual facilities, to nationwide road networks priced with dynamic tolls that vary by vehicle class, time of day, and congestion level. We conclude that the challenge to the expanded implementation of road pricing is less about either pricing technologies or the objectives of pricing, but the politically and economically effective linking of the two.

Key Words: *road pricing technologies, electronic toll collection, technology policy*.

1. Introduction

The surge of road pricing projects in the U.S. and around the globe over the past fifteen years has been enabled by the reliable deployment of a variety of new communications and transportation technologies; technologies that are breathing new life in what is a nearly century-old concept. The idea of road pricing is not new; as early as the 1920s, transportation economists A.C. Pigou and William Knight wrote about the concept and touted the benefits of employing direct user fees to encourage the efficient use of road systems (Wachs 2003). For most of the 20th century, however, a lack of enabling technologies was perhaps the principal obstacle to implementing user fees.[1] Indeed, until the 1990s, most tolls were collected by manned tollbooths, which entailed high labor costs for tolling authorities and high time delay costs for motorists; these costs were often so high as to outweigh the benefits of road pricing. However, the recent rise of new technologies, such as short-range radio transponders and global positioning systems, has made road tolling faster, easier, cheaper, and more reliable.

A number of studies have reviewed various road pricing technologies, mainly as a key component of pricing programs. Small and Gomez-Ibanez (1998) included a brief description of each congestion pricing system, including enforcement technology, in earlier pilot programs as well as a few cases in implementation up to 1998.[2] U.S. National Research Council (1994) and Fielding (1995) reported that most of the basic concerns related to road pricing technologies, such as costs, convenience for drivers, slowing traffic by tolling collection, and privacy intrusion were being overcome by the mid-1990s. Goh (2002) provides details of congestion pricing measures and systems employed in Singapore over the years. The recent technologies provide for a more efficient collection of simple tolls, and also facilitate a movement toward more dynamic, variable user fees, including one for heavy goods vehicles (HGVs), as reviewed by Blythe (2005), Dodoo and Thorpe (2005), and Sorensen and Taylor (2005).

The relationship between the evolution of tolling technologies and road pricing policies is symbiotic: while technologies *enable* the implementation of road pricing policies, transportation pricing policies, in turn, *encourage* the development and use of technologies. That is, specific policy goals equally determine the development of new technology applications and the design of electronic toll collection systems (Worrall 2003). However, system designs tend to evolve based on previous experience, and governments and transportation agencies that have not before tried road pricing tend not to have much basis for selecting appropriate road pricing technologies to meet their policy goals. In order to address this knowledge gap, we examine the linkages between the technical configuration of road pricing systems and relevant policy/pricing issues.

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1 Other causes include public and political acceptance based on concerns with double taxation, privacy, and equity.

2 Cases included those in Singapore, Hong Kong, Cambridge-England, Bergen, Oslo, and Trondheim-Norway, Stockholm-Sweden, Northern France, Orange and San Diego Counties-California, Randstad-the Netherlands, London-England, and Stuttgart-German. Some of these were still in the trial or planning stages at the time of study.

To do this, we analyze information on eight electronic road pricing programs from around the world to identify the set of road pricing technologies adopted and then examine the policy factors related to technology selection. While most US road pricing programs seek to address two main problems—1) worsening traffic congestion in urban areas, and 2) transportation funding shortfalls that have become a major policy concern for the coming years, there are other road pricing policy objectives, particularly in programs in other countries.

Our data are drawn from information provided by tolling authorities and transportation agencies, government reports on the programs/projects, and scholarly research articles. Using information from these various sources, we then examine similarities and differences in policy goals and system design among programs in order to identify technological configurations that may work best in given situations and environments, specifically with regard to policy objectives. Our focus here is on new tolling projects and not on the conversion of existing toll facilities to electronic tolling, because the motivations behind conversion efforts (such as labor cost savings) do not concern the *implementation* of tolling. While the small sample size of this case study approach does not permit us to quantitatively analyze the relationships between tolling technologies and policy objectives, the case study method is appropriate for the questions at hand because they allow for the integration of multiple sources of evidence to investigate contemporary phenomena within a real-world context when the boundaries between phenomenon and context are not clear (Yin 2008).

Following this introduction, we first provide an overview of road pricing technologies that have been used in the field, and then examine the linkages between technological design and relevant policy objectives in eight cases in the US and abroad. After providing details of each of the eight cases within the context, we also discuss challenges and hurdles to future Implementation. We conclude with the summary of our findings and implications for future applications of road pricing.

2. Overview of Road Pricing Technologies

In an earlier phase of this work, members of our research team identified three fundamental technical tasks that are required within any electronic toll collection program for the wide variety of electronic tolling policies and applications (Sorensen 2006). The first task is to *meter road use* (Task 1), and involves determining a vehicle's entry and exit from a tolled facility or general presence in a tolled area. This task also includes measuring distance traveled and/or time of travel, and identifying vehicle characteristics, such as emissions class, weight, and axles in some applications. The second task is to *calculate charges* based on road usage and a rate schedule (Task 2). The third task is to *communicate data* to a collections agency for issuing bills and collecting payment from users; this task may also include measures to prevent evasion and fraud (Task 3). These three fundamental tasks are performed by various combinations of the nine following technologies:

- **On-Board Units (OBU)** are devices of varying complexity, ranging from radio transponders to small computers that can record usage data and calculate fees. OBUs typically provide data storage for vehicle identification information, emissions classification, and axle configuration (Sorensen 2006) as well as computational power and a framework for integrating other technologies, such as wireless communications and global navigation system satellite receivers to determine the vehicle's location, speed, time of travel, and total distance traveled. (Implementing Tasks 1, 2, and 3)

- **Global Navigation System Satellites (GNSS)** are satellite-based systems that can determine a vehicle's position on the Earth's surface in terms of latitude and longitude.[3] This information can be used to monitor facility usage. GNSS has thus facilitated road pricing programs of wide geographic scales (truck tolling programs and distance-based user fees). (Implementing Task 1)

- **Geographic Information Systems (GIS)** are typically stored on OBUs to translate latitude and longitude into a location on the road network. Any road pricing program that relies on GNSS must also incorporate GIS technology as well (Sorensen 2006). (Implementing Task 1)

- **Electronic Odometer Feeds** between a vehicle's odometer and an OBU to measure vehicle miles traveled, and are primarily employed in mileage-based user fee programs. Odometers provide accurate measurements since the vehicle industry has developed them to be relatively tamperproof for warranty reasons. (Implementing Task 1) In some cases, odometer feeds are used as a backup when GNSS signals are lost or they may be the primary means for recording distance (Sorensen 2006).

- **Automated Number Plate Recognition (ANPR)[4]** technology can read digital images of vehicle license plates and translate them into a useable format by computer databases. They are typically used for enforcement purposes in facility and cordon tolling programs, but in London's case it is the primary means of monitoring road use (Blythe 2005). The technology has been continuously improved since it was developed in the 1970s, although photography angles and very reflective license plates are still of particular concern[5] (Redcorn 2008). (Implementing Task 1)

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[3] The United States and Russia currently operate the two satellite networks, named GPS and GLONASS, respectively (May & Sumalee 2003). In addition, the European Space Agency expects to have their Galileo system operational by early 2009 (ESA 2007).

[4] The term "automated license plate recognition (ALPR)" is also commonly used as the systems have to read not only the main characters (letters and numbers) but also the state and any special license plate series. In addition, there are also non-automated versions of plate recognition system.

[5] In the United States, the variety of license plate formats across states and custom vanity plates have reduced the ability of plate recognition software to recognize all characters. In contrast, the

- **Dedicated Short Range Communications (DSRC)** involve short-range microwave or radio communications between vehicles and roadside antennas. DSRC is most commonly used to measure entry and exit of facility or cordon tolling programs, but has been used also for enforcement and billing purposes. The capabilities and costs of DSRC devices can vary significantly, from cheap credit card-sized devices with a range of a few yards to complex radios that can communicate over large distances. DSRC has been a well-suited technology due to its relatively easy installation, its status as a reliable off-the-shelf technology, and is a key element of the majority of existing small-scale electronic road pricing programs in the United States.[6] (Implementing Tasks 1 and 3)

- **Global System for Mobile Communications (GSM)** is cellular communication technology primarily used for travel or billing data transactions. This technology is beginning to appear as an alternative to DSRC in road pricing applications because it does not require an installation of roadside transponders, and is of particular use to complex pricing programs on wide geographic scales (Blythe 2005). (Implementing Task 3)

- **Smart Cards** are credit card-sized devices embedded with a computer chip providing data storage capability, and are primarily used to store and transfer billing data in electronic toll collection programs (Sorensen 2006). They are typically inserted into an OBU and are removed to add money to the user's account or update information. (Implementing Task 3)

- **Supporting Information Technology** includes the Internet, database management systems, and on-line banking protocols that provide the backbone of many electronic toll collection programs. Without these supportive technologies, most road pricing programs would not be as seamless as they are today (Sorensen 2006). (Implementing Tasks 2 and 3)

Despite the wide variety of possible combinations of these technologies, most systems tend to fall under two broad categories, as defined by the primary technology applied to meter road use: Dedicated Short Range Communications (DSRC) and Global Navigation Satellite Systems (GNSS). Systems based on DSRC typically employ roadside readers and in-vehicle transponders that determine when a vehicle enters a particular road segment or area. One simple application of DSRC-based system allows vehicles to pass through open road tolling at higher speeds than conventional manual toll collection, essentially eliminating the need for manually operated tollbooths (Kalauskas, Taylor & Iseki 2008). These systems usually use

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United Kingdom's Driver Vehicle Licensing Authority regulates the format and characters of all license plates nationwide, which ensures greater accuracy from ANPR technology (Gordon 2006).

6 Such as the I-15 HOT Lanes, the SR-91 Express Lanes, the I-394 MnPass Program, and the I-10 Quickride.

roadside cameras and ANPR as a means of enforcement, requiring a lot of street furniture in place (University of Leeds Institute of Transport Studies, 2009). When a vehicle without a transponder passes through the payment point, its license plate is recognized by the system to register the license plate number or send a billing statement by mail to the vehicle owner (Poole 2007). DSRC-based systems have been perceived by road administrations in many countries as the future technology for facility congestion tolls (Blythe 2005).

The second type of system relies on GNSS communicating with on-board units (OBUs) to determine vehicle location. These systems also typically use GSM to communicate data (Blythe 2005). GNSS-based systems rely more on in-vehicle equipment (as well as orbiting satellites) than roadside infrastructure, making system expansion relatively easy.[7] GNSS-based systems are relatively new but are making rapid progress, and have significant potential in various applications of road pricing in the future (Kalauskas, Taylor & Iseki 2008).

A third type uses ANPR as a means to identify vehicles and meter road use for both billing and enforcement purposes. ANPR-based systems have been deployed in the cities of Kristiansand and Bergen in Norway and central London in England (Blythe 2005). ANPR-based systems are advantageous because they do not require on-board units and have no impact on traffic flow, but they have significant difficulties associated with implementation at large scales as well as high transaction costs (Blythe 2005; Institute of Transport Studies University of Leeds, 2009).

3. Applications of Road Tolling Technologies and Policy Objectives

To examine the linkages between primary policy goals and technologies employed, we followed four distinct classes of electronic road pricing programs introduced in an earlier phase of this research (Sorensen & Taylor 2005) and selected two cases for each class in order to have representation of a large variety of road pricing programs:

Four Classes of Road Pricing Programs and Eight Selected Cases

1. Facility Congestion Tolls *(San Diego I-15 HOT Lanes & SR-91 Express Lanes)*
2. Cordon Tolls *(London & Singapore Congestion Toll)*
3. Weight-Distance Truck Tolls *(German Truck Tolling Program & Austria GO Truck Toll)*
4. Distance-Based User Fees *(Oregon Mileage Fee & University of Iowa Road User Study)*

In the analysis of the eight cases, we identified six primary policy goals that are driving factors for the case projects—two or three primary objectives in each program. All systems except the Singapore Congestion Toll have an explicit goal of raising revenue.

[7] A GNSS-based system may still require street infrastructure for enforcement purpose (University of Leeds Institute of Transport Studies).

Six Primary Policy Goals

a) Maximize the usage of underutilized capacity
b) Offer a congestion-free alternative
c) Generate revenue
d) Reduce congestion
e) Allocate costs to users
f) Develop a user-fee alternative to the fuel tax

While road pricing can yield significant benefits and could perhaps be implemented for all of these reasons, we only focus on the immediate objectives of each system as are related to the key motivating factors behind actual implementation and explicitly specified in the documents we reviewed.[8, 9] We also identified two main policy factors that further determine the selection of roadway tolling technologies. Table 1 summarizes these six primary road pricing policy goals, two system decision factors, and types of technologies applied in the eight cases. We discuss details of information presented in Table 1 below.

3-1 Two Major Factors to Link Primary Policy Goals to Technologies Employed

The first major policy decision that influences system specifications is *the geographic scale of the pricing policy*. In most cases, state agencies, transportation authorities, or local/metropolitan governments are responsible for forming policies, planning, and administration of road pricing programs and officials from these organizations must decide the size of the area to be tolled. This can range from as small as an individual facility (i.e. a particular road segment, bridge, or tunnel) or a central business district to as large as an entire state, multi-state area, or an entire nation. The second main policy decision factor is *the complexity of calculating the fee to be charged*. The charges levied ranges from a very simple flat fee to a very complex dynamic toll that varies by time of day, level of congestion, and vehicle type.

8 For instance, regional planners in San Diego had long considered facility congestion tolls as a means to offer a congestion-free alternative as well as optimize HOV lane capacity, but it was only when politicians representing communities along the I-15 corridor saw road pricing as a means to fund transit improvements that the idea had enough support to be implemented (Duve 1994). Thus, we regard revenue generation, maximizing capacity, and offering a congestion-free alternative to be the primary objectives in this case.

9 It should be noted that there are substantial environmental concerns regarding the negative impacts of congestion, air pollution, water pollution, and green house gases related to transportation behind the most of six goals listed here. These concerns are becoming more and more important to justify road pricing schemes especially in Europe (e.g. Stockholm, Switzerland, and Germany).

Table 1: Road Pricing Programs, Policy Goals, and Technologies Employed

Road Pricing Program	**Geog. Scale**	**Level of Complex-ity in Pricing**	**Goals of Pricing Policies:**	**On-Board Units**	**GNSS Receivers**	**GIS**	**Electronic Odometer Feeds**	**ANPR**	**DSRC**	**GSM**	**Smart Cards**	**Support-ing IT**	**Note**
Facility Congestion Toll	Geographically focused	Fee changes according to demand to keep congestion free traffic flow											
San Diego I-15 HOT Lanes			a, b, c	●					●			●	Simple; off-the-shelf technology (OST)
Orange County SR-91 Express Lanes			b, c	●				●	●			●	
Cordon Congestion Toll	Limited scale												
London Congestion Toll		Flat fee	c, d					●				●	Simple (OST), no privacy protection
Singapore Congestion Toll		Variable tolls; protected privacy	d	●				●	●		●	●	Costly infrastructure
Weight-Distance Truck Toll	Large; National scale	Variable tolls; interoperability (German)											
German Truck Tolling Program			c, e	●	●	●			●	●		●	Easy to expand; new technology
Austrian GO Truck Toll			c, e	●				●	●			●	Simple OST; Not easy to expand
Distance-Based User Fee	Large, across facilities and jurisdictions	Variable tolls; a true user fee; high privacy											Need to install sophisticated equipment on all vehicles
Oregon Mileage Fee			c, f	●	●	●	●		●			●	
University of Iowa Road User Study			c, f	●	●	●	●			●		●	

Note: Goals of Pricing Policies: a) maximize the usage of underutilized capacity, b) offer a congestion-free alternative, c) generate revenue, d) reduce congestion, e) allocate costs to users, and f) develop a user-fee alternative to the fuel tax.

While facility congestion toll programs (i.e. the I-15 HOT Lanes and SR-91 Express Lanes) have at least two primary objectives – (b) offering a congestion-free alternative and (c) generating revenue – the principal objective of cordon pricing programs (in London, Singapore, Stockholm, etc.) has been to (d) reduce congestion in the central business district as a clear main objective. The geographic focus of cordon pricing systems has encouraged the adoption of simple and relatively reliable DSRC-based systems that charge users as they enter an individual facility or a defined area.[10] DSRC-based systems generally work best at small geographical scales and can be quickly deployed at a low cost. Building overhead gantries and antennas is relatively easy to do over a small area, and the most rudimentary of these systems require no on-board equipment other than legible license plates; even when vehicle transponders are used, they are relatively inexpensive and require no installation (PB Americas & ECONorthwest 2006; Poole & Orski 2000). Such systems provide for significant flexibility in charging programs as well.

Weight-distance truck tolls and distance-based user fees both seek to generate revenue. In addition, weight-distance truck tolls explicitly (e) allocate costs to road users while the distance-based fee programs (i.e. the Oregon and University of Iowa cases) aim to (f) develop a user-fee alternative to the fuel tax. These types of programs often cover very large areas, such as an entire nation or multiple states. They also involve complex pricing structures to incorporate dynamic user fees by accurately measuring distance traveled, location on the road network, and in some cases, varying the fee based on time of day and level of congestion. In such cases, GNSS-based systems are a dominant technology, while not applied exclusively. Most are GNSS-based, as DSRC-based systems become less practical due to the need to build roadside gantries throughout large road networks. In addition, many GNSS-based systems also employ GIS, GSM, and electronic odometer feeds.

Supporting information technologies such as the internet and online banking protocols play a secondary yet important role in all of the cases reviewed here. In addition, OBU's are found in all of the cases that employ DSRC-based or GNSS-based systems (London being the sole exception).

3-2 Secondary Factors to Influence Technology Choices

In addition to geographic scale and the complexity of the pricing program, a few other factors influence system specifications and the selection of technologies.

[10] The London Congestion Toll (cordon pricing) deploys a network of cameras and ANPR technology to impose a very simple flat fee per day with a very short implementation time. This is different from the DSRC-based system in Singapore, which has a long history of tries and errors of road pricing, can now charge variable fees based on congestion levels. The difference in applied technologies between these two cases is a reflection of the level of complexity of pricing policy.

Tradeoff between Speedy Implementation and Complexity of Technologies

Generally speaking, the more complex the pricing policy, the more complex the system, which often leads to longer development and implementation phases (and vice versa). Older technologies are more established and reliable, and can be taken "off-the-shelf" for implementation rather easily. Such "off-the-shelf" technologies may inhibit innovation by establishing a precedent, whereby replicating existing technologies is both less risky politically and has the advantage of interoperability with existing systems.[11] At the same time, they are more limited in terms of the range of policies that can be implemented and geographic scales at which they can be applied. In contrast, newer and more advanced technologies have more capability of implementing various pricing options over much larger geographic areas. For example, large-scale GNSS-based systems allow for facility or area-specific policies to be incorporated into an overarching road pricing program.

Future Expansion

There are a number of reasons why policymakers may want to physically expand pricing programs in the future. For instance, congestion may worsen outside of the tolled area or motorists may take unpriced routes to avoid paying tolls. As systems begin to incorporate larger geographic scales, DSRC-based systems become less practical and very costly due to the need to build roadside gantries throughout the road network (Sorensen 2006). In contrast, GNSS-based systems can easily enlarge its tolled road network through simple reprogramming.

Ease of Communicating Charges and Price Structure

Clear communication of price structures and charges is central to creating a comprehensible and politically acceptable road tolling system. Given the complexity of dynamic road pricing systems that may aim to influence travel behavior at the margins, such clear, comprehensible communication can be a tall order. While no "best" way of framing prices and presenting charges has emerged, road tolling programs have put considerable effort into incrementally improving the ways that they present this information to the motoring public.

Privacy

An underlying concern in relation to technology application is the issue of privacy. However, we have seen progress in system designs to better address privacy concerns in the examined cases. Privacy protection is typically accomplished through dispersing personal information, vehicle attributes, and distance data across various system platforms and technologies and encryption of data. GNSS-based systems often raise concerns that government agencies can track individuals, however, it should be noted that in such systems, the OBU only *receives*

[11] Interoperability is the ability of a technology, a system, or a product to work with others without special efforts, improvements or modifications on the part of users. Standardization of technology and interoperability are important determinants for choosing technologies. There is a path-dependent effect on the technology choice in subsequent projects within the same jurisdiction, region, and nation after an initial selection in the earlier projects, as was the case with FasTrak in California and EZ-Pass in the Northeastern and Midwestern states in the US. Interoperability gives great convenience to customers as well as reduces the costs of owning and maintaining separate equipment and accounts for both customers and tolling agencies.

GNSS information and uses this to locate itself, rather than vehicles being continuously tracked (Wachs 2006). The use of data encryption protects private data from being eavesdropped and decoded by unauthorized parties (University of Leeds Institute of Transport Studies, 2009). In addition, a survey study by Ison (2000) found that more than half of respondents from local authorities, academics, and transport interest groups said that they were “very/fairly unconcerned” with “invasion of road user privacy”, further suggesting that newer system designs have adequately addressed such concerns.

3-3 Case Analysis

In order to illustrate the linkage between policy objectives, important system design factors, and applied technologies, we discuss each of the eight selected road pricing programs and assess the level of success.[12] Overall, all of these road pricing programs have achieved their initial goals, while they went through different levels of difficulty in technology implementation. Although examples within each program generally share a common system design, each instance has a different story relevant to the specific suite of technologies employed.

Facility Congestion Tolls

Facility congestion tolls are on an individual segment of the road network, and charge tolls that vary by the level of congestion. While tolling individual facilities is not new, varying the toll level to guarantee free flowing traffic conditions in the toll lanes has only been implemented within the last two decades in the United States. This idea has been particularly successful when applied as a means to provide the option of uncongested travel in the midst of severe congestion. These high occupancy toll (HOT) lanes typically allow high occupancy vehicles (HOV) to enter for free, while single occupancy vehicles (SOV) are allowed to use the excess HOV lane capacity for a price. Two prominent examples of HOT lanes are found in Southern California—the I-15 HOT Lanes in San Diego and the SR-91 Express Lanes in Orange County. In both cases, the facilities operate independently, part of no overarching road pricing network. Thus they employ relatively simple DSRC-based systems focused on electronic toll collection only within the HOT lanes to offer a congestion-free alternative and generate revenue.

San Diego’s I-15 HOT Lanes

The San Diego Association of Governments initiated a HOT lanes demonstration project between 1996 and 1999, converting two reversible HOV lanes in the median of I-15 in northern San Diego County that were initially opened in 1988 but had been underutilized (SANDAG 2007). Along with the initial goal of HOV lanes to offer a time savings incentive to carpoolers, generating revenue for transit improvements by tolls was the key to the support of a local elected official for the conversion from HOV to HOT (Duve 1994; Smirti et al. 2007). Following a

[12] Due to limited space, we could not provide detailed descriptions of the eight cases mentioned in this paper, and had to focus on most relevant information to support our points. For a more detailed description of these cases, please refer to a series of PATH reports, which are available from http://database.path.berkeley.edu/reports/index.cgi.

successful implementation, the HOT lanes continued to operate since the end of the demonstration project (SANDAG 2007).

The electronic toll collection program was designed around the original 8-mile lanes. The lanes are barrier-separated throughout their entire length, and monitoring facility usage is thus a relatively simple task to accomplish using DSRC technology at one location. A set of overhead gantries equipped with short-range antennas is placed at the middle of the lanes.[13] Solo drivers wishing to buy into the lanes must purchase a FasTrak[14] windshield-mounted transponder (OBU) before use (SANDAG 2007). Vehicles pass underneath the gantries at high speeds while the gantry antennas briefly communicate with the transponder. From this transmission, centralized computers deduct the toll from the user's prepaid account as well as use the information to monitor the quantity of vehicles using the facility (Commission for Integrated Transport 2006).

If too many vehicles start entering the lanes such that the overall traffic speed is expected to decrease, the centralized computers automatically modify the toll[15] every six minutes to reduce the number of entering vehicles and maintain a level of service C (or fewer than 27 vehicles per lane per mile) (Brownstone et al. 2003).

SR-91 Express Lanes

The SR-91 Express Lanes were built in 1995 and initially operated by a private firm, and consist of four lanes (two in each direction) in the median of a ten-mile stretch of the SR-91 freeway in Orange County (OCTA 2007). The Orange County Transportation Authority (OCTA) used a public-private partnership scheme to offer congestion relief without spending taxpayer money. The concept of the lanes evolved into HOT lanes in order to generate revenue for private investors (Boarnet & Dimento 2004).

The SR-91 Express Lanes operate very similarly to the I-15 HOT lanes with a limited access facility with no overarching road pricing system in place, and use the same DSRC technology with overhead gantry-mounted antennas and FasTrak transponders to collect the toll and maintain a congestion-free flow.

There are a few differences between the SR-91 Express Lanes and I-15 HOT lanes worth noting. First, the toll is not dynamic like the I-15 toll, but determined by a toll schedule[16] that the toll authority sets every three months for any given hour on any day of the week, based on

[13] While repairing the overhead gantries requires the lanes to be closed, mounting the antennas above is preferable to the sides due to better communication with the transponder (FHWA 2003).

[14] The same FasTrak transponder can be used on the I-15 HOT lanes, or any other FasTrak facility in California (OCTA 2007).

[15] The price typically varies between 50 cents to $4, and increases to as high as $8 on occasions of extreme congestion (SANDAG 2007).

[16] Currently, the price ranges from $1.20 during off peak periods to $10.00 between 3 pm and 4 pm on Fridays (OCTA 2007).

historical data. Secondly, the SR-91 Express Lanes have established different pricing structures for frequent users and discounts for carpoolers and disabled drivers.[17] DSRC technology can identify unique users, and these flexible pricing structures are relatively easy to implement by storing additional information to each account in the system. Thirdly, the SR-91 Express Lanes employ ANPR technology as a means of enforcement. If a SOV without a transponder passes underneath the gantry, a picture is taken of its license plate. With this information, the SR-91 Express Lanes can access the address associated with the plate number to mail a bill (VTA 2005).

Assessment

Both the I-15 HOT lanes and the SR-91 Express Lanes have been successful in improving overall person throughput, offering a reliable congestion-free alternative, and generating revenue (Smirti et al. 2007). The I-15 HOT lanes also successfully maximized the usage of underutilized capacity—the total number of vehicles using the HOT lanes increased by 66 percent between 1998 and 2006 (SANDAG 2007). In addition, both systems relied on off-the-shelf technology that led to easy implementation.[18] Because of the private sector's desire to protect their revenue flow, the SR-91 system is designed better in enforcing payment than the I-15 HOT lanes.[19] Following these successes, expansion plans of the I-15 and SR-91 facilities as well as bringing similar programs to other corridors in San Diego (SANDAG 2007) are currently underway.

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[17] For instance, vehicles with three or more passengers can usually travel free on the lanes but must pay 50% of the fare during the Friday peak period, and people who plan to use the lanes more than 20 times a month can travel for $1 less during each trip by buying a "91 Express Club" account (OCTA 2007).

[18] While both the I-15 and SR-91 facilities are barrier separated, it is feasible to design facility congestion tolls around non-barrier separated lanes. However, extra precautions may be required to enforce the toll. For instance, the SR-167 HOT Lanes in Washington only utilize a double white line to separates the tolled lane from the general purpose lanes. In order to ensure that SOV vehicles do not attempt to merge into the lanes without paying the appropriate fee, the tolling authority has subsidized the Washington State Patrol to provide additional manual enforcement. These officers have been equipped with handheld enforcement readers that can determine whether or not a vehicle's transponder has communicated with an overhead gantry to pay the toll (Rubstello 2007). Additionally, as the lack of a physical barrier places the HOT lanes much closer to the general purpose lanes, there have been concerns about the system erroneously charging drivers who may own transponders but are driving in the free lanes. While field tests have suggested that the technology is precise enough to avoid this confusion, the designers of the SR-167 HOT Lanes chose to place additional DSRC receivers above the adjacent general purpose lanes as an extra precaution. Thus, as vehicles with transponders pass underneath gantries above the adjacent free lanes, the system will recognize that they are not in the tolled lane, and not charge them the fee (personal communication with Patty Rubstello of the WSDOT Urban Corridors Office on October 22, 2009).

[19] Highway patrol officers provide manual enforcement of the toll as the I-15 HOT system currently lacks means to automatically cite toll violators. The system can alert highway patrol officers when there has been a violation in the current system, but plans are underway to implement a more automated method using ANPR (SANDAG 2006).

Cordon Tolls

Cordon tolls are charged for entering or driving within a geographically enclosed area, such as a central business district (CBD), with the primarily goal of reducing vehicular traffic congestion in the area, applying a simple economic principle: the higher the price of a good, the lower the demand for the good. Cordon tolls apply to anyone who drives inside the zone, though often with numerous exemptions. The technical approaches taken to cordon pricing vary. An examination of two prominent examples, in London and in Singapore, reveals that more complex system designs can provide for more flexible pricing policies and user privacy.

The London Congestion Toll

The London Congestion Toll program began in 2003 with the aim of reducing congestion within central London[20] to protect its economic vitality and to provide revenues to improve transit services. Transport for London (TfL) manages the toll, which is currently set at £8 (US $16) to enter the zone, enforced between 7 a.m. and 6 p.m., Monday to Friday. Drivers can pay using the internet, at kiosks within the zone, at certain retail establishments, and with their cell phone.

London's system is based on a relatively simple ANPR-system. A network of 340 stationary and mobile cameras continuously takes pictures of license plates of vehicles within the zone. Plate numbers in these pictures are processed by ANPR software, and compared to a database of people who have paid the toll.[21] To address privacy concerns, TfL deletes the images the day after the person pays the toll, or keeps them for 13 months when the charge is not paid within two days (TfL 2007a).[22] The centralized management of user information provides TfL with flexibility in pricing structures through individual accounts. Policies include a 90% discount for residents of the zone and exemptions for the disabled (TfL 2007b).

The simplicity of the system design has its advantages and disadvantages. The use of ANPR, an established technology, was a safe bet as there was little uncertainty to implementing the system itself. Relying primarily on cameras and ANPR also does not require drivers to purchase any equipment prior to use – a boon to infrequent users and visitors. However, the program does not easily provide for a variable charging schedule based on congestion levels and/or time of day. While current policy may be trying to keep the plan simple enough for the public to understand, the system's ability to encourage or discourage driving within the cordoned area during certain times of day is indeed limited (Santos 2008; Santos 2005). In addition, critiques of the program point out the low reliability of the system in detecting number

[20] The cordoned area includes major centers of government, law, business, finance, and entertainment, and was expanded westward in 2007.

[21] Because the plate number links the vehicle to the owner, the collection agency can pursue the driver until all charges have been paid.

[22] TfL also has an agreement providing law enforcement agencies access to available images as long as the request is for a legitimate purpose (TfL 2007a). "Legitimate purposes" are defined under the Data Protection Act of 1998. It is worth noting that the Metropolitan Police Service is subject to certain exemptions of this act for the purposes of national security (and not general crime) (TfL 2007a).

plates in bad weather conditions, high transaction costs (about 50 percentage), the increased rate of license plate thefts, and an increase in the number of drivers qualifying for the substantial discount in relation to the cordon area expansion that resulted in increased traffic congestion and relative reduction in revenue.

Singapore's Electronic Road Pricing Program

The evolution of Singapore's congestion toll over the last three decades exemplifies how technology facilitates more efficient operations and direct user fees. Singapore is an exception in having been adopting a number of policies to reduce vehicular traffic within the CBD even before road pricing technologies were available since the 1970s when its automobile ownership rate began to dramatically increase. Singapore's programs started with vehicle purchase permits and passes to enter into a cordoned area, shifted in 1995 to a road pricing scheme with a flat fee, and, after experiencing some practical difficulties such as spillover congestion and costly manual enforcement, introduced the Electronic Road Pricing (ERP) Program in 1998. ERP employs a DSRC-based system with wide network of overhead gantries on all entry points to the tolled area, OBUs with DSRC receivers, and ANPR cameras for enforcement purposes (Goh 2002).

In addition, prepaid smart cards used with the transponder store payment information as well as individual account information. Drivers can add money to their account balance at retail outlets, banks, kiosks (Goh 2002) as well as online, and can also use the cards to pay for a variety of other goods and services including parking, retail purchases, and vending machines (Networks for Electronic Transfers 2007). The transponders contain vehicle information, such as class and weight, which ERP uses to charge a variable price. ERP can also change the toll prices based on point of entry and time of day. This provides ERP with the ability to use more variable pricing—possibly based on the estimated costs each driver imposes on other drivers and society—to manage routes as well as at a certain time of day (which the London Congestion Toll cannot do) (Santos 2005). If one route is in particularly high demand during the morning peak, for instance, they can set the toll to be high on the main route while lowering prices on alternative routes, encouraging more efficient use of the road network (Goh 2002).

Assessment

Both cordon tolling programs have been successful in achieving its goals. In London, the initial 2003 policy reduced traffic by 33 percent, increased speeds by 14 to 20 percent, and reduced excess waiting times for buses by 33 percent, and generated a total revenue of £123 million ($US $248 million) that has been reinvested into transit improvements (Small 2005, Turner 2003).[23] Critics of the London Congestion Toll point to high administrative costs (totaling to roughly half of the total revenue collected) as well as a gradual reduction in average speeds over time. Indeed, the cost to maintain a comprehensive network of roadside cameras is high. However, average speeds have fallen not because the number of total vehicles has slowly risen

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[23] As Small (2005) notes, decreasing automobile traffic through pricing may also create a perpetual "virtuous cycle" of cost savings and ridership increases to transit.

(and it has, in fact, remained relatively level), but rather because road space has been reallocated to buses, pedestrians, and cyclists (Santos 2008). The ERP system in Singapore has dramatically improved efficiency and lowered operating costs, compared to the old systems, although installing the DSRC, ANPR, and smart card infrastructure was a costly endeavor (Santos 2005). Within its first year of operations, ERP resulted in increased travel speeds on the CBD and on the expressways, a 16 percent increase in average bus speeds, and a successful spreading out of traffic over the course of the day (Goh 2002).

In the London system, the public expressed considerable privacy concerns (i.e. the “big brother” perception) associated with the installation of a network of cameras and centralized management of user information (despite the limitations TfL has placed on access to vehicle location data) (Litman, 2006). In contrast, Singapore’s ERP system stores personal data on the smart cards, rather than a centralized processing center, and also spreads the electronic toll collection tasks over various technologies, separating detailed personal information from billing data and collecting it only when required (May & Sumalee 2003).

Weight-Distance Truck Tolls

Weight-distance truck tolls levy fees on trucks to internalize the costs that they impose on the road network, using vehicle information, such as weight, location, and emissions class. Electronic weight-distance truck tolls are particularly popular in European nations because they can ensure that foreign truckers passing through will pay their fair share in fees. Programs in Germany and Austria use GNSS-based systems and DSRC-based systems, respectively, to accomplish the same goals of generating revenue and equitably distributing the costs of road use to drivers. The two programs represent both ends of the spectrum in the technological sophistication– from complex programs providing for considerable flexibility in pricing policies to those employing simple and reliable technologies, if at the cost of flexibility, illustrating the advantages and disadvantages of both approaches.

Germany’s Truck Tolling Program

As the development of the European Union has furthered economic integration among the member nations, Germany experienced significant growth in truck traffic, a great deal of which is comprised of foreign vehicles traveling through (May & Sumalee 2003), and this raised a concern regarding the use of public funds to maintain the quality of the road network. In 2005, Germany launched a truck toll system, an ambitious and technologically sophisticated road pricing program for goods movement within the country administered by a private entity, Toll Collect (Toll Collect 2007). The main goals of the system were to implement direct user fees, raise revenue, and institute an emissions-related toll. The tolls apply to heavy goods vehicles, defined as trucks over 12 tons, to shift the burden of finance from taxpayers to the freight industry. Toll income has been earmarked for transportation infrastructure, including rail improvements to encourage a mode shift of goods movements.

The system employs on-board units equipped with GNSS receivers and digital road network maps, which determine the location of the truck, keep track of distance traveled, calculate the appropriate charges (averaging 15 cents/kilometer), and communicate this billing data to the collection agency via GSM. Various enforcement methods are employed, including DSRC communications between the OBU and roadside units.[24] Most trucks participate in the electronic payment program although a manual payment system remains for vehicles without OBUs (Toll Collect 2007). The inclusion of both DSRC and GNSS-based systems ensures interoperability in the future as the rest of Europe decides between the two systems as a common format for road tolling programs (Ruidisch 2004).

This system design provides considerable flexibility in charging policies. The OBU stores vehicle-specific information allowing fees to be levied on weight (via number of axles) and emissions class, encouraging lighter and cleaner vehicles via price signals (Toll Collect 2007).[25] GNSS technology allows distance charges on a kilometer basis. Since little roadside infrastructure is needed, it is easy to expand the network of priced roads to include adjacent roads that truckers may eventually use in order to avoid tolls (Bolte 2003).

Austria's GO Truck Tolls

Austria's electronic tolling program was launched in 2004, with the two primary goals of raising revenue and charging freight vehicles for the costs they impose by traveling on Austrian highways (of particular concern is the high cost of maintaining tunnels and bridges along the Austrian Alps) (Schwarz-Herda 2005). Austria's GO program employs a relatively simple DSRC-based system including in-vehicle transponders and a network of over 800 overhead gantries equipped with antennas throughout the highway network (Dodoo and Thorpe 2005).[26] As trucks pass underneath the gantries, the toll is deducted through a simple transmission between the gantry and the transponder. One hundred of these gantries are equipped with enforcement devices that include vehicle classification systems (that identifies trucks from passenger automobiles) and ANPR cameras that can enable the tolling authority to identify vehicle owners when trucks pass underneath the gantry without a valid transponder reading (Schwarz-Herda 2005).

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[24] While GNSS is the primary technology used to meter road use, the system designers of this program also installed roadside receivers to communicate with on-board DSRC transponders to verify that trucks using tolled roads participate in the tolling program. Gantries are equipped with: 1) vehicle detection and profiling that distinguish trucks, 2) antennas that communicate vehicle OBUs, and 3) OCR cameras to obtain truck license plate numbers. In addition, vans are also used on the autobahns to supplement the limited gantry system for the enforcement purpose.

[25] Heavier and more polluting vehicles are charged higher tolls than cleaner ones; the heaviest and most polluting vehicles are charged approximately 50% higher tolls than the lightest and cleanest (Toll Collect 2007).

[26] The Swiss system uses a similar DSRC-based technology.

Assessment

Both Germany's program – a GNSS-based system – and Austria's – a DSRC-based system – have succeeded in raising transportation revenue and allocating costs to users.[27] However, the differences between each system illustrate the tradeoff between ease of implementation and complexity as well as the need to plan for future system expansion. In the German case, the considerable risk of implementing new technologies was exemplified by a delay of two years and budget overruns.[28] In contrast, depending on a reliable technology kept Austria from similar problems during the implementation period. However, both Germany and Austria have experienced significant problems with trucks diverting to local streets (which are not designed to withstand heavy truck traffic) to avoid tolls (Rothengatter 2004; Schwarz-Herda 2004). While Germany's GNSS-based system can simply be reprogrammed to include these local streets, Austria's DSRC-based system is difficult to physically expand as it requires gantries to be installed on additional segments of the road network. Thus, while Germany's system came only after a great deal of delay and additional expense, it is likely that the benefits of a geographically flexible GNSS-based system will eventually outweigh these costs.

Distance-Based User Fees

Distance-based user fees charge all vehicles on the road network a fee that is proportional to distance traveled. Two demonstration projects of distance-based user fees are currently under development in Oregon and the University of Iowa. Both programs developed GNSS-based systems with the primary goals of generating revenue and developing a user-fee program to replace the fuel tax, while dynamic fees are also possible.[29]

Oregon Mileage Fee Concept

Facing declining revenue from the current state gas tax, the Oregon Department of Transportation (ODOT) put together a Road User Fee Taskforce to research and develop a mileage based user fee system to eventually replace the gas tax. The task force established several criteria for the new system:

- Accurately measure distance traveled
- Be technically feasible and reliable with minimal evasion potential
- Differentiate travel between zones as well as time of day
- Place a minimal burden on motorists and the private sector
- Provide for a seamless transition

[27] At the same time, truckers try to optimize their routing and minimize road user charges in various ways, such as using secondary roads, although its magnitude turned out not to be as substantial as the governments was afraid since costs associated with using secondary roads (time, fuel, maintenance) offset the savings.

[28] The German government initially cancelled the contract with Toll Collect, but reinstated it under the agreement that Toll Collect would pay the German government for the revenues it would have collected, had the system kept on schedule (Samuel 2004).

[29] As a fee based on distance traveled is a better proxy of damages caused on roadways than the consumption of fuel, it will more equitably distribute the costs of road use to drivers.

- Respect privacy concerns of the public
- Have low administrative costs

The task force partnered with universities to develop the Oregon Mileage Fee Concept. Each vehicle was equipped with an on-board unit that included a dashboard display, a GNSS receiver, a DSRC communicator, and an electronic odometer feed primarily used to measure miles traveled. The GNSS receiver was used to distinguish which miles were driven in certain tolling zones, so that the appropriate fees could be levied (Whitty 2007). The OBU also continuously kept track of charges owed, and payments were made during the refueling process. Fueling stations were equipped with DSRC radios and communicated with the OBU automatically. DSRC was chosen over GSM for this task for its lower costs, greater reliability, and provisions for greater privacy.

From April 2006 to April 2007, nearly 300 volunteers and two service stations in Portland participated in a pilot program, in which the distance fees were automatically added to the cost of fuel in exchange of subtracting the state gas tax during the fuel transaction. The receipt showed the separate amounts for fuel and user fees. If there was no DSRC transmission between the fueling station and the vehicle, either due to the absence of the appropriate equipment or attempts to tamper with it, then the usual state gas tax was charged (Whitty 2007). Overall, the pilot project demonstrated that technologies are capable of electronically determining and collecting user fees.

University of Iowa Road User Study

Under a joint funding partnership between the Federal Highway Administration and 15 state departments of transportation, transportation researchers at the University of Iowa have been working on a mileage based user fee system for automobiles and trucks. The program's objective is primarily to replace the motor fuel tax with distance-based fees.

An OBU in the vehicle contains a GNSS receiver, a GIS map file, a rate schedule, and an electronic odometer feed, which in concert determine a vehicle's location within a jurisdictional billing zone and measure miles traveled to compute total charges (Forkenbrock 2005). Vehicles are also equipped with a GSM transmitter that communicates the appropriate charges to a billing center on a monthly basis. This center will issue charges and collect payment through a variety of options such as billing statements or prepaid accounts (Kuhl 2007).

As this program's system is designed to operate across many states and quite possibly at the national level, it has a greater focus on flexible charging capability allowing different rates for different jurisdictions (Forkenbrock 2005). The system is also capable of being dynamically updated with new boundaries and charging policies. The system also includes the ability to incorporate additional transportation policies, such as congestion tolls, variable charges based on emissions class, and fee adjustments for trucks based on weight. Fees and taxes can be simultaneously collected at the local, state, and federal level as well (Kuhl 2007).

The University of Iowa team is currently testing the technology to ensure smooth operations and examine the potential to implement the program nationwide (University of Iowa Public Policy Center 2008). A field test with 1,200 participants in six regions (San Diego, Boise, Austin, Eastern Iowa, Baltimore, and the research triangle in North Carolina) began in January of 2009 and is scheduled to finish in August of the same year.[30] The researchers will evaluate the system design and collect attitudinal data, and then proceed with a second testing phase with another 1,200 volunteers.

Assessment

It is too early to gauge the success of large-scale distance-based user fees as most are not yet ready for full implementation. However, pilot programs have yielded promising results (Sorensen & Taylor 2006).

In general, Oregon's program was successful and demonstrated its ability to meet the aforementioned goals. However, the OBU and fuel station devices were not available off-the-shelf and had to be developed from scratch, and a few minor problems arose in the pilot program. First, some OBUs simply did not work or significantly drained the car battery. Secondly, the service station operators experienced difficulty in incorporating the experimental billing equipment with their own. Lastly, station owners stated that they would require greater reliability with the fuel pump devices as well as a means to offset the additional costs associated with accounting.[31] These components need slight modifications for smoother operations in a wider implementation setting (Whitty 2007).

Both programs have a large degree of flexibility to compute fees based on various variables to achieve certain policy goals. The pilot project in Oregon indicated that a more complex network of spatial zones with more flexible time schedules is feasible, and that environmental concerns can also be met by charging variable rates based on the emissions class of each vehicle. The user fee can also be pegged to an index in order to protect the revenue stream from inflation. In addition, the University of Iowa program has incorporated great potential for pricing flexibility and scale into its system.

In both programs, respecting user privacy is a paramount concern as many fear it may be possible to track individuals with orbiting satellites. Oregon's system protects privacy by delegating different tasks over multiple technologies and devices in a way that personal information, vehicle attributes, and distance data are dispersed across various system platforms. No agency – billing, administrative or otherwise – can link an individual to his or her travel behavior (Whitty 2007). In the University of Iowa Road User Study, user privacy was secured through an embedded security key for user authentication and data encryption. Furthermore, the system uploads the total charges per user separate from the distribution of those charges by

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30 According to Paul Hanley of the University of Iowa (personal communication, January 27, 2009).

31 The researchers note that this kind of issue was primarily due to the pilot nature of the program.

jurisdiction; under this program, it will be impossible to tell where users have been (Forkenbrock 2005).

Three Challenges to Future Implementation

While all eight electronic road pricing programs reviewed here met their immediate objectives, there remain challenges for broader implementation with respect to phasing, accuracy, and equity.

Phasing

As current transportation revenues (based mainly on fuel taxes) continue to decline in relative terms, the need to find alternatives grows increasingly urgent. The GNSS-based systems developed by Oregon and the University of Iowa hold enormous potential to change the nature of transportation finance by collecting fees from users, but installing the necessary equipment on the entire vehicle fleet is a daunting task.

A simple strategy would be to require auto manufacturers to include GNSS receivers and other associated equipment on every new car and truck rolling off the production line. Based on sales and scrappage rates for automobiles and trucks, it would take about 20 years for 95 percent of all vehicles to have the required technology (Forkenbrock 2005). The cost of equipment would be substantially reduced in mass production (Whitty 2007), and the additional cost for auto manufacturers to install the equipment is estimated to be on the order of $100 (Sorensen 2006).[32] In addition, it may be possible to modify and use existing GNSS receivers and GIS files on vehicle navigation units (Forkenbrock and Hanley 2006) and/or smart phones equipped with GSM and GNSS technologies (Kitchen 2008, Blythe 2005) in a GNSS-based toll system.[33] Such approaches might be more cost-effective than installing similar equipment for the sole purpose of road pricing.[34] At the same time, Kitchen (2008) argues that road pricing requires more trusted equipment in a more secure system than such after-market devices can provide, and that a dedicated system is necessary to protect both the user and tolling authority from intended or unintended fraud.

Accuracy

A secondary technical problem is that existing GNSS networks location accuracy limitations in the range of 10-15 meters, which restricts their ability to toll road links in dense networks and in

32 The cost to develop prototype equipment is high (about $400 per vehicle in the Oregon example).

33 Obviously, current devices do not have capability of calculating and collecting a toll.

34 We can find a precedent of the use of after-market devices in California. Caltrans' Vehicle-Infrastructure Integration (VII) concept envisions a statewide system where vehicles equipped with in-vehicle displays, GNSS receivers, and DSRC could communicate with a similar set of roadside equipment, including electronic toll collection as one of over 100 uses of such a system. In a demonstration project, SafeTrip-21, Caltrans utilized GNSS-enabled smart phones because of the very high cost of installing an original infrastructure. Project leaders hope that the pilot project will demonstrate the benefits of VII and result in additional resources in the future (Larson 2008).

dense high rise urban environment (May & Sumalee 2003; University of Leeds Institute of Transport Studies, 2009), unless another technology such as an electronic accelerometers and odometer feeds are used. However, GNSS is still a rapidly developing technology, and it is likely that the problem of accuracy will eventually be overcome (Grush 2008; Samuel 2009).

Equity

As wide-scale implementation of GNSS-based toll systems will undoubtedly take some time, a transition system must allow those with or without the equipment to pay the distance-based user fee and the fuel tax, respectively, as is designed in the Oregon Mileage Fee concept (Forkenbrock 2005; Forkenbrock & Hanley 2006; Whitty 2007). For purposes of equity, many argue that the user fee should not differ greatly from the gas tax (Forkenbrock 2005). And, rather than mandates, transportation authorities might also encourage drivers to retrofit their vehicles with the necessary equipment via incentive programs that significantly discount the user fee in a way that is financially beneficial to users.

4. Conclusion

The technologies reviewed in this article all collect tolls more efficiently than manual collection (Al-Deek, Mohamed & Radwan 1997; Pietrzyk & Mierzejewski 1993), and allow for a wide variety of tolling applications. In this paper, we examined the linkages between six policy objectives and technology configurations in eight electronic road pricing programs in the US and abroad, and in doing so have identified two primary policy goals that are considered in selecting particular road pricing technologies. Two most important of these are: (1) the geographical scale of road network tolled and (2) the level of complexity of pricing programs. That is, as the geographical scale and fee complexity increase, system designs generally become more elaborate and require incorporation of newer technologies. In our examination of the linkages between technological design and relevant policy/pricing issues,

Table 2 summarizes the linkages between road pricing policy goals and electronic roadway tolling technologies. Facility and cordon pricing programs have been motivated primarily by three policy objectives—*maximizing underutilized capacity, offering a congestion-free alternative*, and *reducing congestion*—and have usually been based on a DSRC-system, which are relatively simple and effective over small, clearly defined areas. Two other policy objectives—*allocating costs to users* and *developing a user-fee alternative to the fuel tax*—are more common to two other kinds of pricing programs: weight-distance truck tolls and distance-based user fees; these are often based on GNSS-based systems, which can cover large areas and allow for varying fees.

Table 2: Present Linkages between Road Pricing Policy Goals and Technologies Employed

	Main Technologies			Supporting Technologies					
Road Pricing Policy Goals	**GNSS Receivers**	**DSRC**	**ANPR**	**On-Board Units**	**GIS**	**Electronic Odometer Feeds**	**GSM**	**Smart Cards**	**Supporting IT**
Small Geographic Scale Programs (Facility Congestion Tolls & Cordon Tolls)									
(a) Maximize the Usage of Underutilized Capacity	⅄	●		❍/⅄	⅄	⅄	⅄		❍/⅄
(b) Offer a Congestion-Free Alternative	⅄	●	❍	❍/⅄	⅄	⅄	⅄		❍/⅄
(d) Reduce Congestion	⅄	●	❍	❍/⅄	⅄	⅄	⅄	❍	❍/⅄
(c) Generate Revenue	⅄	●	❍	❍/⅄	⅄	⅄	⅄		❍/⅄
Large Geographic Scale Programs (Weight-Distance Truck Tolls & Distance-Based User Fees)									
(e) Allocate Costs to Users	●		⊙	❍	❍	⅄	❍		❍
(f) Develop a user fee alternative to the fuel tax	●		⊙	❍	❍	❍	❍		❍
(c) Generate Revenue	●			❍	❍	❍	❍		❍

● Primary technology to meter road use (defining tech. of system)
❍ Secondary Technology
⊙ Technology partially incorporated
⅄ Technology that is not currently used, but is likely to be adopted in future

We also found four secondary factors—*tradeoff between speedy implementation and complexity of technologies*, *options for future expansion*, *ease of communicating charges and price structure,* and *privacy*— also influence technology choice. Revenue generation was a motivation in all of the programs reviewed, save Singapore, which lays bare the increasing pressure on governments to find new, reliable streams of revenue for the construction, operation, and maintenance of transportation infrastructure. As concerns with the phasing and accuracy of GNSS technologies will likely to fade with time, electronic road pricing systems can be designed to protect people's privacy by ensuring that travel behavior data cannot be linked to personal information without prior consent. Such developments notwithstanding, the "Big Brother" association that tolling connotes for some seems to likely persist.

It appears likely that transportation agencies wishing to implement electronic toll collection on individual facilities and/or cordon level will continue to employ DSRC-based systems, at least in the short term.[35] Looking ahead, continued progress in the design and operation of GNSS will make it easier and less risky to implement in widening variety of applications. So over time, while costs associated with advanced technology and phase-in strategies in implementation are certainly valid concerns, it is likely that well-designed GNSS-based systems are likely to become capable of processing varying user fees at larger scales and increasingly commonplace. If jurisdictions begin to see larger scale road pricing as a potent revenue generator, we could expect to see more regional or even statewide GNSS-based systems over time. Indeed, planners in both London and Singapore are considering upgrading to GNSS-based systems to increase both the geographic scale and pricing flexibility of their systems (Schindler 2007; TfL 2006).

Given the current, severe fiscal crises in road finance, ongoing efforts to mitigate chronic traffic congestion, and waxing concerns with both the local and global environmental effects of driving, electronic road pricing systems are likely to grow in scale as well as in number in the coming years. While systems with the latest technologies are continuously in development, a wide variety of tolling technologies are now available to implement pricing to address a wide range of policy objectives. This continuously declining level of constraints and concerns in tolling technologies was revealed in the survey of needs assessment among decision makers from 21 European cities that are interested in pursuing road pricing in the CURACAO study; respondents ranked technology seventh out of nine in importance (University of Leeds Institute for Transport Studies, 2009). Our aim here has been to excavate the linkages between these tolling technologies and policy goals because in our view the principal challenge to road pricing implementation today is neither the means (tolling technologies) nor the ends (public policy objectives), but the effective linking of the two.

35 The report prepared in the ProGR€SS project provides conclusion about road pricing technology to support this. This report recommends to use more mature technologies, DSRC and/or ANPR, in an urban area in the very near future, taking into account a cost and ease of implementation, as GPS-based systems are not mature enough to always work properly for full-scale implementation (PROGRESS, 2004).

Acknowledgements

This research conducted for this article was supported by grants from the California Partners for Advanced Transit and Highways (California PATH) program and the California Department of Transportation (Caltrans); the authors are grateful for this support. This work draws on earlier phases of this research conducted by faculty and students at UCLA and UC Berkeley. This article draws in particular on work conducted by former UCLA students Rebecca Kalauskas and Paul Sorensen; the authors owe a particular debt of gratitude to Dr. Sorensen for earlier work on this topic. Special thanks go to members of the project technical oversight committee and Caltrans staff, as well as Karen Trapenberg Frick at California PATH for helpful comments and suggestions on earlier stages of this research. We also thank anonymous reviewers for valuable information and comments on the earlier version of this paper. The views presented and any errors or omissions are the sole responsibility of the authors, and not those of the funding agencies.

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