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TASK A-3: Examining the Linkages between Electronic Roadway Tolling Technologies and Road Pricing Policy Objectives

California PATH Project—Task Order 6330

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Abstract

The surge of road pricing projects in the U.S. and around the globe over the past fifteen years has been enabled by a set of new communication and transportation technologies. There is currently a wide array of technical configurations ranging from systems based on "tried and true" short-range radio communications to experimental systems relying on global positioning satellites. These technologies provide for a more efficient collection of simple tolls, and also facilitate a movement toward more dynamic, variable user fees.

In this study, we provide a comprehensive literature review of eight road pricing cases to identify types of tolling technologies employed, given various policy objectives. In particular, we examine two examples from each of four types of road pricing programs: 1) facility congestion tolls, 2) cordon tolls, 3) weight-distance truck tolls, and 4) distance-based user fees. In the selected cases, we specifically examine various suites of technologies and evaluate approaches to their implementation in road pricing programs with regards to system design and policy.

In our literature review, we first describe three major technical tasks to be performed—metering road use, calculating charges, and communicating data—that are implemented by a set of nine technologies varying from on-board units to global navigation system satellites. Secondly, we identify six primary policy goals of these road pricing systems: a) maximize 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.

In our careful synthesis of the literature, we find that two main policy decisions most often determine the selection of roadway tolling technologies: (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 tolling individual facilities with flat fees, to nationwide road networks priced with dynamic tolls that vary by vehicle class, time of day, and congestion level. Taking into account the severe funding shortfall for transportation infrastructure, serious concerns about traffic congestion, and related adverse environmental impacts, we expect electronic road pricing systems to continue to grow in scale as well as in number. While systems with newer technologies are continuously in development, the most difficult hurdle for road pricing programs is now less of technical feasibility, but rather political and public support for implementation.

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

Executive Summary

The surge of road pricing projects in the U.S. and around the globe over the past fifteen years has been enabled by a set of new communications and transportation technologies. These technologies provide for a more efficient collection of simple tolls, and also facilitate a movement toward more dynamic, variable user fees. The relationship between the evolution of tolling technologies and road pricing policies is symbiotic; while technologies *enable* implementation of road pricing policies, transportation pricing policies, in turn, *encourage* the development and use of technologies.

This report is part of a larger study examining the various economic, institutional, operational, and political factors influencing the implementation of electronic roadway tolling around the world to help decision-makers in California weigh the pros and cons of expanded implementation in the Golden State. In this report, to identify the linkages between technological design and relevant policy/pricing issues, we examine various suites of technologies and approaches to implementation in eight road pricing programs found around the world.

We organize our analysis around four distinct classes of road pricing programs, and draw on two examples for each type:

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 "Toll Collect" & Austria GO Truck Toll)*
4. Distance-Based User Fees *(Oregon Mileage Fee & University of Iowa Road User Study)*

Facility congestion tolls are designed around an individual segment of the road network, and charge tolls that vary by the level of congestion. Cordon tolls are charged within an enclosed area, such as a central business district, to limit the number of automobiles entering the area and reduce congestion. Weight-distance truck tolls levy fees on trucks to internalize the costs that they impose on the road network. Finally, distance-based user fees charge all vehicles on the road network a fee that is proportional to distance traveled.

From the review of these case studies we find two main policy decisions that most often determine the selection of roadway tolling technologies: (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 tolling on individual facilities with flat fees, to nationwide road networks priced with dynamic tolls that vary by vehicle class, time of day, and congestion level. Within all of these road pricing programs, there are three distinct technical tasks to be performed: metering road use, calculating charges, and communicating data. To perform these tasks, systems rely on a set of nine technologies:

- **On-Board Units (OBU)** that are in-vehicle devices of varying complexity, ranging from radio transponders to small computers
- **Global Navigation System Satellites (GNSS)** that can determine latitude and longitude on the Earth's surface

- **Geographic Information Systems (GIS)** that are used to translate latitude and longitude into a location on the road network
- **Electronic Odometer Feeds** measure vehicle miles traveled and transfer the data between a vehicle's odometer and an on-board unit
- **Automated Number Plate Recognition (ANPR)** that can take a photo of a license plate and convert it into digital text
- **Dedicated Short Range Communications (DSRC)** that involve short-range microwave or radio communications between vehicles and roadside antennas
- **Global System for Mobile Communications (GSM)** that is essentially satellite based cellular communication technology
- **Smart Cards** that are credit card-sized devices embedded with a computer chip providing data storage capability
- **Supporting Information Technology** that include the Internet, database management systems, and on-line banking protocols that provide the backbone of many electronic toll collection programs

Despite the wide variety of possible combinations of these technologies, most systems tend to fall under two broad categories that can be characterized 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 and in-vehicle transponders that determine when a vehicle enters a particular road segment or area. The simplest form of these DSRC-based systems employs windshield-mounted transponders allowing vehicles to pass through open road tolling at higher speeds, essentially eliminating the need for manually operated tollbooths. While the DSRC-based system is easier to implement, it places most of the required technical infrastructure roadside, making it costly to install over large geographical scales.

The second type of system relies on GNSS communicating with on-board units to determine vehicle location. GNSS-based systems rely more on in-vehicle equipment (as well as orbiting satellites) than roadside infrastructure, making system expansion relatively easy. GNSS-based systems are relatively new but are making rapid progress, and have significant potential in various applications of road pricing in the future.

From our review of the eight case studies, we observe some patterns between road pricing systems, policy goals, and technologies employed. In particular, we identified six primary policy goals: a) maximize underutilized capacity, b) offer a congestion-free alternative, c) generate revenue, d) reduce congestion, e) allocate costs to users, and f) replace the fuel tax. Another key consideration for all factors is the geographic scale at which the pricing policy is directed. The following table describes the key characteristics of each case study as well as the patterns between pricing programs, policy goals, and technologies employed in the eight reviewed cases

.

Table ES-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	Dynamic fee to keep congestion free traffic flow											Simple; off-the-shelf technology (OST)
San Diego I-15 HOT Lanes			a, b, c	●					●			●	
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 Toll Collect			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	●	●	●	●			●		●	

Goals of Pricing Policies: a) maximize 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.

Facility congestion toll programs have the primary goals of raising revenue and offering a congestion-free alternative while cordon congestion tolls aim to reduce overall congestion. To accomplish this, a road pricing system needs to charge users as they enter an individual facility or a defined area. DSRC-based systems generally work best at these small geographical scales, and can be quickly deployed at a low cost; building overhead gantries and antennas is relatively easy to do in a small area, and on-board transponders are inexpensive and easily installed. These systems provide for significant flexibility in charging programs as well.

However, as systems begin to incorporate larger geographic scales, DSRC-based systems become less practical due to the need to build roadside gantries throughout the road network. These road pricing programs, weight-distance truck tolls and distance-based user fees, also have the common policy goal of raising revenue. In addition, weight-distance truck tolls seek to allocate the full cost of road use to the driver. This may involve measuring a variety of factors such as distance traveled, time of day, vehicle class, and congestion levels. Furthermore, distance-based user fee trials in the United States have the primary goal of developing user fee alternatives to the fuel tax. Because of the large geographic scale and complexity of the fee to be charged, GNSS-based systems are better suited to these applications.

An underlying concern in many cases examined here is the issue of privacy.[1] However, in all examples where privacy was of particular consideration, system designers have been able to take appropriate steps to protect personal information. This is typically accomplished through the use of smart card technology or by dispersing personal information, vehicle attributes, and distance data across various system platforms. While it is uncertain if it is possible to lose the "Big Brother" association altogether, the public should nevertheless be assured that electronic road pricing systems are designed in such a way that travel behavior data cannot be linked to personal information without prior consent.

We have noted that GNSS technology is rather new, and that GNSS-based systems currently take longer to implement. However, as interest in large-scale GNSS-based road pricing programs grows among policymakers, they will become a more proven and more easily implemented technology. One current limitation is that GNSS that may be off by as much as 15 meters in its positioning, and needs backup technologies for more accurate measurements. However, new developments in this technology may fix this problem, making GNSS-based systems the logical choice for most road pricing projects in the future. Another question that still remains regarding GNSS-based systems is how to phase in the necessary equipment throughout the vehicle fleet, but this is primarily due to the fact that all domestic systems are still in the pilot stages. As more jurisdictions begin to see larger scale road pricing as a potent revenue generator as well as a congestion management tool that can incorporate smaller scale policies, we expect to see more region or even statewide GNSS-based systems in the future.

All of the fully operational electronic toll collection systems examined in this report have been successful in fulfilling their primary objectives. In addition, experiments of domestic GNSS-based systems that seek to replace the fuel tax are promising. In general, the sentiment is that technical feasibility is no longer a problem in facilitating the policy goals for road pricing

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[1] In this paper, we focus primarily on privacy as it relates to system design issues. The greater issue of privacy with regards to public acceptance will be covered in greater detail in a later phase of this research.

programs. That is, road pricing’s limiting factor is no longer technology, but rather political and public support for implementation.

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1. Introduction

The surge of road pricing projects in the past fifteen years has put us on the brink of what some call a "renaissance" in electronic road tolling applications (Sorensen & Taylor 2006). This report is part of a larger study examining the various economic, institutional, operational, and political factors influencing the implementation of electronic roadway tolling around the world to help decision-makers in California weigh the pros and cons of expanded implementation in the Golden State. In the first phase of this research (Kalauskas, Taylor & Iseki 2008), we identified a multitude of factors contributing to the rise in electronic toll collection, one of which is a new set of communication and transportation technologies.

This paper provides a comprehensive literature review to examine the linkages between technological design and relevant policy/pricing issues. To do so, we synthesized information from reports by tolling authorities, transportation agencies, and academic research articles to describe the status of road pricing technologies as well as examine the policy factors related to technology selection. More specifically, we review the set of new technologies and investigate eight cases to illustrate what programs have in common as well as the diversity of policy goals and system design.[2] In particular, we examine the pros and cons of various technologies and approaches, the possibility of changes in these pros and cons stimulated by the arrival of new technologies, and technological configurations that work best in given situations and environments, specifically with regard to policy objectives.

All of the road pricing programs examined here have been successful in achieving their primary policy goals, and we do not intend to minimize these achievements. Most issues that arise concern secondary matters and long-term issues such as privacy and system expansion. That said, each system certainly has its pros and cons and we evaluate each approach with regards to system design and policy.

Without a doubt, these technologies are transforming the concepts of road pricing into reality. Transportation economists A.C. Pigout and William Knight wrote about road pricing as early as the 1920s, 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 prevented the implementation of these user fees. For example, the most state of the art means of toll collection was the manned tollbooth, which was so cumbersome that in many cases, its high labor and time costs outweighed the benefits of road pricing. As a result, jurisdictions established a proxy for the user fee – the motor fuel excise tax. However, the gas tax was acknowledged as a second best solution, as it did not fulfill all of the criteria for a direct user fee (Wachs 2003). After many decades of the gas tax serving as an approximation of a user fee, we have recently observed the rise of new technologies, such as short-range radio transponders and global positioning systems, which provide for a return to toll collection programs that incorporate the user fee. Electronic toll collection also represents a potential new revenue source that has coincided with increasing fiscal shortfalls within the transportation sector.

[2] We selected seven cases that were already referenced in Tasks A-1 and A-2 (so as to build upon them) and one new case that is not included in the previous tasks – we found it necessary to include the University of Iowa's Road User Study in order to provide a diversity of system design for similar policy objectives.

Inflation and the improving fuel economy of the vehicle fleet, combined with a political failure to raise fuel taxes to keep up with the needs of transportation systems, have led to what Wachs (2006) terms a "quiet crisis in transportation finance."

These technologies provide a more efficient collection of current tolls as well as the ability to collect new ones. Worrall (2003) describes the relationship between road pricing technology and policy as an iterative process; while these technologies certainly enable policies, specific policy goals equally determine the development of new technology applications and the design of electronic toll collection systems. That is to say, transportation policy also drives the use and development of these technologies in road pricing applications. The two primary policy decisions that determine system design are (1) the geographical scale of road network tolled, and (2) the complexity of the fee collected. Regarding the geographical scale, pricing policies range from tolling a specific segment or facility (i.e. tunnels and bridges) to an entire corridor. The charges levied can also be quite simple, such as a flat fee, or quite complex, such as a dynamic toll that varies by vehicle type, time of day and level of congestion. Generally speaking, as the geographical scale and fee complexity increase, system designs become more elaborate and require incorporation of newer technologies.

Although there are various possible combinations of geographical scale and fee complexity, four distinct categories of distinct road user electronic charging programs emerge from available cases. We have classified our findings according to the following programs introduced by Sorensen (2006):[3]

(1) Congestion tolls on individual facilities
(2) Congestion charges for cordoned areas, such as a central business district
(3) Weight-distance truck tolls
(4) Distance-based user fees applied to an entire road network

These road pricing programs have distinct policy goals and different system designs, but present varying levels of success. Facility and cordon congestion tolls have been implemented in many cities and, by and large, have accomplished their goals admirably. Electronic weight-distance truck tolls have had mixed technical results, although they have met their immediate objectives. 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). 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. In most cases, the type of management – a public, public-private partnership, or private project – has little effect on system design.

In this report, we examine the enabling technologies and their application to road pricing programs. Following the introduction, we provide an overview of electronic roadway tolling (road pricing) technologies. In the third section, we examine eight cases around the world in which the tolling technologies have been adopted or under experiment, with particular attention to goals set for pricing policies. In the fourth section, we discuss our findings, synthesizing

[3] Throughout this report, we draw a significant amount of information from an earlier UCLA Institute of Transportation Studies report by Sorensen (2006).

information from the eight cases. The last section summarizes our findings in the study and provides a few remarks regarding technology implementation.

In summary, from our examination of the eight cases, we identify six primary policy goals that exhibit some patterns in road pricing systems and technologies employed. 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 explicitly specified in the documents we reviewed.[4] Thus, these goals are not present in every project, and most examples tend to have only two or three of these primary objectives:

a) Maximize 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

In selecting particular road pricing technologies, we find the geographic scale at which the pricing policy is directed and the level of complexity of pricing programs to be particularly important. We also find that newer technologies, Global Navigation Satellite Systems in particular, (more commonly known as GPS in the U.S.) enable road pricing policies to be implemented at larger geographic scales and a return to charging programs that incorporate the user fee. While GNSS-based systems have not yet been implemented in the U.S., it is conceivable that such a road pricing program (at either the state or national level) would be able to incorporate many of the smaller scale tolling systems that exist today. One question that remains regarding GNSS-based systems is how to phase in the necessary equipment throughout the vehicle fleet, but this is primarily due to the fact that all domestic systems are still in the pilot stages. As Global Navigation Satellite Systems technology is still rapidly developing, it is likely that its applications within electronic road pricing will grow in the future.

2. Overview of Technologies

Because different technological approaches to road pricing have led to varying levels of success, it is necessary to review the array of technologies employed by these programs. Despite the wide variety of electronic tolling policies and applications, there are certain technical tasks that are required within an electronic toll collection program. These new technologies facilitate more efficient operations of these tasks, which, in turn, enable new pricing policies. Sorensen (2006) defines these tasks:

[4] We interpret the immediate objectives to be related to the key motivating factors behind actual implementation (as described in Task A-1). 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.

- **Meter road use.** This task involves determining a vehicle's entry or exit from a tolled facility or general presence in a tolled area. In some cases, it may also involve measuring distance traveled and/or time of travel as well as vehicle identification, emissions class, weight, and/or axles.

- **Calculate charges.** Road usage is compared to a rate schedule to determine charges owed.

- **Communicate data.** Billing data are transmitted to a collections agency for issuance of bills, and payment is collected from the users. Some measures are taken to prevent evasion and fraud.

From Sorensen (2006), we identified nine technologies that have played a significant role in enabling electronic toll collection. Each technology has a function within an electronic road pricing system, and there are no systems based solely on one technology. Some technologies are mature, while others have emerged only recently. Table 1 shows the three broad technical tasks in electronic toll collections systems, and the technologies used to implement each task. A description of each item follows the table.

Table 1: Tolling Technologies Classified by Application

Technology	Metering Road Use	Calculating Charges	Communicating Data
On-Board Units	●	●	●
GNSS	●		
GIS	●		
Electronic Odometer Feeds	●		
ANPR	●		
DSRC	●		●
GSM			●
Smart Cards			●
Supporting IT		●	●

Source: Sorensen (2006)

- ***On-Board Unit (OBU).*** This term applies to a device that is installed on board users' vehicles. It typically provides data storage, computational power, and a framework for integrating other on-board technologies, such as global navigation satellite system receivers and wireless communications. For simpler systems such as the I-15 HOT lanes, the OBU may simply serve as a radio transponder, while for more complex systems like German Toll Collect it typically records usage data and calculates charges owed. OBU's may also store vehicle identification information, emissions classification, or axle configuration (Sorensen 2006).

- ***Global Navigation Satellite Systems (GNSS).*** GNSS is a satellite-based system that can determine the position of an object in terms of latitude and longitude on the Earth's surface. 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). In road pricing programs, OBU's typically have GNSS receivers to determine the vehicle's location, speed, time of travel, and total distance traveled. While some systems rely heavily on roadside equipment to monitor facility usage, GNSS employs satellite and OBU's to perform this task. GNSS has thus facilitated road pricing programs of wide geographic scales, namely truck tolling programs and distance-based user fees. However, the accuracy of existing GNSS networks is limited to 10-15 meters (May & Sumalee 2003). This restricts their ability to toll road links in dense networks, unless another technology such as an electronic odometer feed is used as well. In addition, some slight misrepresentations of such system designs have sparked concerns that GNSS continuously track the vehicles. But as Wachs (2006) points out, vehicles are not tracked at all. Rather, the OBU only *receives* GNSS information and uses this to locate itself, not the other way around.

- ***Geographic Information Systems (GIS).*** In order to translate latitude and longitude information from GNSS receivers into a vehicle's location on the road network, OBUs need digital road maps stored in GIS format. Any road pricing program that relies on GNSS must also incorporate GIS technology as well (Sorensen 2006).

- ***Electronic Odometer Feeds.*** Electronic links between OBU's and the odometer serve as a means to measure distance traveled and are primarily employed in mileage-based user fee programs like the Oregon Mileage Fee. Since the vehicle industry has developed odometers to be relatively tamperproof for warranty reasons, odometers can be relied upon to deliver accurate measurements. 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).*** ANPR 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. The technology was developed in the 1970s, and has been continuously improved since, although photography angles and very reflective license plates are still of particular concern (Redcorn 2008).

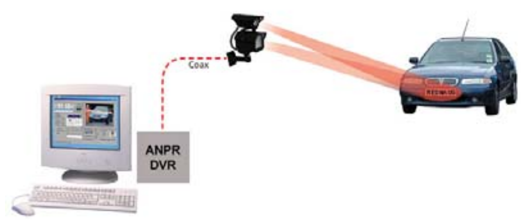

Figure 1: ANPR Technology (Rednaus Industrial Design & Control)

- ***Dedicated Short Range Communications (DSRC).*** DSRC involves short range microwave or radio communications between vehicles and roadside antennas. It is most commonly used to measure entry and exit of facility or cordon tolling programs, although some systems use DSRC for enforcement and billing purposes as well. DSRC has proven to be a reliable off-the-shelf technology, and is a key element of most electronic roadway pricing systems in the United States (such as the I-15 HOT Lanes, SR-91 Express Lanes, I-394 MnPass Program, and the I-10 Quickride). Since the majority of existing electronic road pricing programs have been designed around small areas and individual facilities, DSRC has been a well-suited technology due to relatively easy installation. However, as pricing policies begin to cover larger geographic areas, DSRC begins to lose its practicality due to the high cost of installing roadside transponders across the road network (Sorensen 2006).

Figure 2: Roadside antenna communicates with vehicle-mounted transponder via DSRC (TransNet 2008)

- ***Global System for Mobile Communications (GSM).*** GSM is essentially satellite based cellular communication technology. While it has existed in the communications industry for some time, it is beginning to appear as an alternative to DSRC in road pricing applications because it does not require the installation of roadside transponders. Thus, it is of particular use to complex pricing programs on a wide geographic scale like the German Toll Collect system, and is primarily used to communicate travel or billing data.

- ***Smart Cards.*** Smart cards are credit card-sized devices embedded with a computer chip providing data storage and transmission capability. While they have a multitude of uses both within and outside of the transportation sector, they 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, as seen in the Singapore ERP program.

- ***Supporting Information Technology.*** A wide variety of information technologies, such as the Internet, database management systems, and on-line banking protocols, 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).

The primary challenge in selecting technologies and designing a road pricing system is the need to balance ease of implementation with flexibility in charging options. Older technologies are generally more established and reliable, and they can be taken "off-the-shelf" for implementation in road pricing rather easily. At the same time, these older technologies tend to have more limitations in terms of the range of policies that can be implemented, and are better suited to applications at smaller geographical scales. In contrast, while newer technologies are relatively less proven for their capability and reliability, they hold greater potential in the range of pricing options. Systems that are more complex and employ newer technologies also tend to cover larger geographic scales and provide more flexibility in charging programs. In their decision to choose which technologies to employ, policymakers and system designers must often make a tradeoff between ease of implementation and complexity of the system.

Despite the wide variety of possible systems designs, most tend to fall under two broad categories that can be characterized by the primary technology applied to meter road use: DSRC and GNSS.

DSRC-based systems typically employ roadside and in-vehicle transponders that determine when a vehicle enters a particular road segment or area. The simplest form of these DSRC-based systems employs windshield-mounted transponders allowing vehicles to pass through open road tolling at higher speeds, essentially eliminating the need for manually operated tollbooths (Kalauskas, Taylor & Iseki 2008). These systems usually use roadside cameras and ANPR as a means of enforcement. 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). While the DSRC-based system is easier to implement, it places most of the required technical infrastructure roadside, making it costly to install over large geographical scales.

The second type of system relies on GNSS communicating with OBUs to determine vehicle location. GNSS-based systems usually involve an additional technology such as an electronic odometer feed to ensure accuracy in determining vehicle location and travel distance. GNSS-based systems rely more on in-vehicle equipment (as well as orbiting satellites) than roadside infrastructure, making system expansion relatively easy. 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).

In general, facility and cordon area congestion tolls employ DSRC-based systems while weight-distance truck tolls and mileage-based user fees are designed around GNSS-based systems. This is, however, a loosely fitting characterization, as there are prominent exceptions. For instance, the Austrian GO Truck Toll is a weight-distance truck toll that employs a DSRC-based system while the London Congestion Toll, a cordon area program, does not use a DSRC or a GNSS system at all.

While DSRC and GNSS are primary technologies found in most road pricing programs, the combination of other technologies varies. In the next section, we describe the applications of road tolling technologies and the suitability of various systems to policy goals.

3. Applications of Road Tolling Technologies

In order to illustrate the diversity of technologies employed, we examine the relationship between system design and policy goals in eight road pricing programs found around the world. For each of the four types of road pricing, we draw on two case. The I-15 HOT Lanes and SR-91 Express Lanes are both facility congestion tolls in Southern California and use DSRC-based systems to offer a congestion-free alternative and generate revenue. Cordon congestion tolls in London and Singapore both have the primary goal of reducing congestion in a CBD, although they do so through different technical approaches. Similarly, weight-distance truck tolls in Germany and Austria similarly 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. Lastly, we draw on two demonstration projects of distance-based user fees in Oregon and the University of Iowa that have both developed GNSS-based systems with the primary goals of generating revenue and equitably distributing the costs of road use to drivers. Table 2 classifies the cases by system type.

Table 2: Cases by System Type

DSRC-Based	GNSS-Based	ANPR-based
▪ San Diego I-15 HOT Lanes ▪ Orange County SR-91 Express Lanes ▪ Singapore Electronic Road Pricing Program ▪ Austria GO Truck Toll	▪ German Toll Collect ▪ Oregon Mileage Fee ▪ University of Iowa Road User Study	▪ London Congestion Charge Zone

Facility Congestion Tolls

While tolling individual facilities is not new, varying the toll level to guarantee free flowing traffic conditions 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 San Diego and Orange County, California. In both cases, the facilities operate independently, with no overarching road pricing network. Thus they employ relatively simple systems focused on electronic toll collection within the HOT lanes only.

San Diego's I-15 HOT Lanes

In 1988, two reversible HOV lanes were opened in the median for 8 miles of I-15 in northern San Diego County. The goal of these HOV lanes was to offer a time savings incentive to carpoolers. However, it became quickly apparent that these lanes were underused, and the San Diego Association of Governments selected this facility for a HOT lanes demonstration project between 1996 and 1999 (SANDAG 2007). Also key to the conversion from HOV to HOT was the support of an elected official representing a community along the I-15 corridor, who saw the tolls as a means to generate revenue for transit improvements for his constituency (Duve 1994). The implementation of the HOT lanes has been quite successful and they have continued to operate since the end of the demonstration project (SANDAG 2007).

As the lanes were already in place when the HOT lanes policy was implemented, the electronic toll collection program was designed around these 8-mile lanes. Because the lanes are barrier-separated throughout their entire length (and thus only have one point of entry and one point of

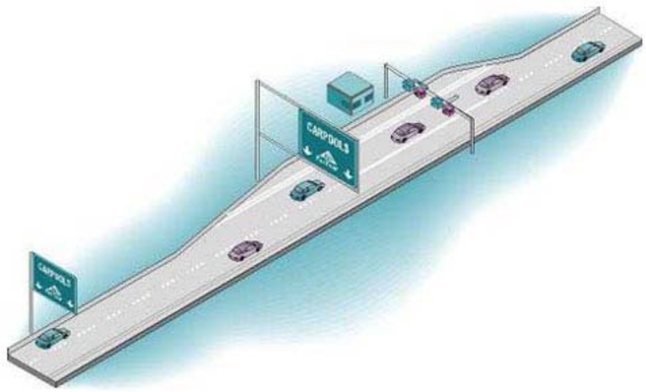

Figure 3: I-15 FasTrak System (SANDAG 2007)

exit), monitoring facility usage is 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.[5] Solo drivers who wish to buy into the lanes must purchase a FasTrak windshield-mounted transponder before use (SANDAG 2007). A few miles before the HOT lanes begin, drivers are alerted to the price via electronic displays placed on the side of the road, and if they choose to use the lanes, they can take the appropriate on-ramp. 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). Carpoolers with a transponder simply need to place the device into an anti-static bag that inhibits communication with the gantry antenna so that the toll will not be charged (VTA 2005).

If too many vehicles start entering the lanes such that the overall traffic speed is expected to decrease, the centralized computers automatically raise the toll to reduce the number of entering vehicles. The price can be modified every six minutes, and requires no manual input or authorization. In general, the toll is kept high enough to maintain a level of service C (or fewer than 27 vehicles per lane per mile) (Brownstone et al. 2003). The price typically varies between 50 cents to $4, and increases to as high as $8 on occasions of extreme congestion (SANDAG 2007).

The I-15 HOT lanes have been very successful in achieving their primary goals of maximizing underutilized capacity and offering a congestion-free alternative. Between 1998 and 2006, the total number of vehicles using the HOT lanes increased by 66 percent (SANDAG 2007), and the system has been able to maintain a reliable option for travelers. In addition, a portion of the toll revenue generated by the I-15 HOT lanes has been used to completely fund transit improvements along the same corridor (SANDAG 2007). Technically speaking, the system was relatively easy to implement and maintain. One downside to the current design is a lack of 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. The success of the I-15 HOT lanes has led to an expansion of the I-15 facility as well as bringing similar programs to other corridors in San Diego (SANDAG 2007).

Key Characteristics:

- Geographically focused system design
- Dynamic tolling system to keep congestion free traffic flow

[5] 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).

Goals of Pricing Policies:

- Maximize underutilized capacity
- Offer a congestion-free alternative
- Generate revenue (for transit)

Pros:

- Using simple off-the-shelf technology (DSRC) led to easy implementation

Cons:

- Lack of means to automatically cite toll violators

SR-91 Express Lanes

The SR-91 Express Lanes were opened in 1995 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. The Orange County Transportation Authority (OCTA) had planned to construct HOV lanes on the SR-91 but continuously lacked the funds to do so. In order to offer congestion relief without spending taxpayer money, the OCTA allowed a private firm to build and operate the lanes in the early 1990s (OCTA 2007). 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. They are a limited access facility with no exit or entry for the entire ten miles, and there is no overarching road pricing system in place. The use of lanes is also variably priced so that a congestion-free flow is maintained. The SR-91 Express Lanes use the same DSRC technology to collect the toll; users must purchase a windshield-mounted FasTrak radio transponder that communicates with an overhead gantry-mounted antenna.[6] Users are alerted to the toll price a few miles before the lanes begin. Should they choose to use the lanes, drivers simply pass underneath the gantry and the toll is deducted from their account (Boarnet & Dimento 2004).

There are a few differences between the SR-91 Express Lanes and I-15 HOT lanes worth noting. First and foremost, although the use of lanes is variably priced, this pricing is not dynamic like the I-15 toll that is updated every six minutes. Instead, the toll authority establishes a toll schedule that determines the price for any given hour on any day of the week. The prices are established using historical data, and can be modified every three months. Currently, the price ranges from $1.20 during off peak periods to $10.00 between 3 pm and 4 pm on Fridays (OCTA 2007). Secondly, the SR-91 Express Lanes have established different pricing structures for frequent users and discounts for carpoolers and disabled drivers. 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). 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

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

information, the SR-91 Express Lanes can access the address associated with the plate number to mail a bill (VTA 2005).

The SR-91 Express Lanes have also been quite successful in improving overall throughput, offering a congestion-free alternative, and generating revenue (Sorensen 2006). Because of the private sector's desire to protect their revenue flow, the system is designed to be slightly more successful in enforcing payment than the I-15 HOT lanes. Like the I-15 HOT lanes, expansion plans for the SR-91 Express Lanes are currently underway.

Key Characteristics:

- Geographically focused system design
- Static, but flexible tolling system to keep congestion free traffic flow
- Use of ANPR technology provides for efficient enforcement

Goals of Pricing Policies:

- Offer a congestion-free alternative
- Generate revenue (to construct new capacity)

Pros:

- Using simple off-the-shelf technology (DSRC & ANPR) led to easy implementation

Cons:

- Perhaps a dynamic toll would manage lane capacity more efficiently

Cordon Tolls

Cordon tolls charge users for entering or driving within a geographically enclosed area. While facility congestion tolls only apply to those who elect to use them, cordon tolls apply to anyone who drives inside the zone primarily to reduce congestion within the enclosed area, typically a central business district. However, technical approaches taken to accomplish this goal vary. An examination of two prominent examples, in London and in Singapore, reveals that cordon tolling is generally successful in achieving its goals although more complex system designs can provide for more flexible pricing policies and user privacy.

<u>The London Congestion Toll</u>

The London Congestion Toll program began in 2003 with the aim of reducing congestion within central London to protect its economic vitality and to provide revenues to improve transit services. The cordoned area includes major centers of government, law, business, finance, and entertainment, and was expanded westward in 2007. 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. A network of 340 stationary and mobile cameras continuously takes pictures of license plates of vehicles entering, exiting, and traveling within the zone. The pictures are fed to a central data center where ANPR software reads the plate numbers, and these records are compared to a database of people who have paid the toll. Because the plate number links the vehicle to the owner, the collection agency can pursue the driver until all charges have been paid. To address privacy concerns, TfL deletes the images the day after the person pays the toll. However, if the charge is not paid within two days, TfL keeps a copy of the image for 13 months. 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).[7] Although ANPR technology is rather simple itself, the centralized management of user information provides Transport for London with flexibility in pricing structures through individual accounts. Policies include a 90% discount for residents of the zone and exemptions for the disabled (TfL 2008).

The simplicity of the system design has its advantages and disadvantages. ANPR 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. In addition, while the program allows flexible pricing structures, it does not easily provide for a variable charging schedule based on congestion levels and/or time of day as seen on the I-15 and SR-91 HOT lanes. 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 (Sorensen 2006).

Nonetheless, the congestion pricing program has been wildly successful in achieving its goals, and the use of an established technology (ANPR) was instrumental in implementing a reliable system. Within the zone, the initial 2003 policy cut automobile traffic by 33 percent, increased speeds by 14 to 20 percent (Small 2005), and reduced excess waiting times for buses by 33 percent (Turner 2003). Toll revenue, amounting to a net £123 million ($US $248 million) has been reinvested into transit improvements. As Small (2005) notes, decreasing automobile traffic through pricing also creates a perpetual "virtuous cycle" of cost savings and ridership increases to transit. However, there are considerable privacy concerns 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, the "big brother" perception still prevails and many claim their privacy has been invaded. As Litman (2006) notes, privacy may be particularly problematic concern in London's case due to the existence of surveillance systems in many British cities.

Key Characteristics:

- Flexibility in pricing structures through individual accounts
- Simple system design with high reliability
- No up-front cost to drivers
- No capability for flexible pricing

Goals of Pricing Policies:

- Reduce congestion (to protect economic vitality)
- Generate revenue (for transit)

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[7] "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).

Pros:

- Using simple off-the-shelf technology (ANPR) led to easy implementation
- Easy for drivers to use

Cons:

- Cannot vary price by particular route, time of day, or level of congestion
- Camera system and centralization of user information raises privacy concerns

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. While many jurisdictions have adopted road pricing to take advantage of enabling technologies, Singapore started experimenting with such programs before the process was as seamless as it is today. Facing a dramatically rising automobile ownership rate since the 1970s, Singapore pursued a number of policies to reduce vehicular traffic within the CBD in order to protect its economic vitality. Such policies required the public to obtain permits for vehicle purchase and drivers to buy passes in order to enter into a cordoned area of downtown. Although it reduced traffic within the area, congestion spilled over onto the roads leading up to the zone. In 1995, the Singaporean government implemented the Road Pricing Scheme that charged users a flat fee to enter downtown as well as use the expressways and feeder streets leading into the zone. While successful, the policy relied on manual enforcement and proved to be burdensome and expensive to administer (Goh 2002).

In 1998, Singapore introduced the Electronic Road Pricing (ERP) Program, replacing all previous road tolling programs. In order to alleviate concerns about centralized management of personal information, ERP spreads the electronic toll collection tasks over various technologies, collecting detailed personal information only when required. ERP employs a wide network of DSRC overhead gantries on all entry points to the tolled area. Each vehicle that travels into the zone must have a DSRC transponder that communicates with antennas on the gantries, and violators are caught using ANPR cameras.

Payment information is stored on neither the transponder nor a centralized processing center, but on prepaid smart cards that are inserted into the transponder. These smart cards store the individual account information, and agencies only access personal information in the case of insufficient funds or the lack of a transponder. Individuals 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). Storing personal data and billing information on the smart cards rather than a centralized processing center has been key in alleviating privacy concerns (May & Sumalee 2003)

Figure 4: Transponder and Smart Card (EPVIS 2002)

While the smart cards manage the billing and personal information, the transponders contain information about the vehicle, such as class and weight, which ERP uses to charge a variable price. In addition, ERP can change the toll prices based on point of entry and time of day. This provides ERP with the ability to manage routes via prices. 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. This encourages more efficient use of the road network, maintaining high speeds, reliable travel times, and lower vehicle emissions (Goh 2002).

ERP has been the most successful of Singapore's road pricing programs. The vehicle purchase permits and paper passes only indirectly approached user fees, but ERP sends direct price signals to inform drivers of the costs they impose on other drivers and society by driving a certain vehicle on a particular route at a certain time of day (which the London Congestion Toll cannot do). And while installing the DSRC, ANPR, and smart card infrastructure is a costly endeavor, the ERP system has achieved improved efficiency and lower operational costs than the old imprecise manual enforcement method. Singapore's previous tolling policies achieved certain reductions in auto usage and congestion, which ERP was able to further. 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).

Key Characteristics:

- Dynamic toll varies by route, time of day, and level of congestion
- Smart cards store personal information and protect privacy
- DSRC transponders store vehicle information used to charge variable tolls

Goals of Pricing Policies:

- Reduce congestion (to protect economic vitality)

Pros:

- Ability to vary the toll based on point of entry and time of day makes it possible to manage the level of traffic on routes in the road network via prices
- Privacy is protected by diffusing different tasks to different technologies

Cons:

- Relies on costly infrastructure

Weight-Distance Truck Tolls

Although many jurisdictions currently levy fees to reflect the damage caused by trucks on roadways, most programs used do not directly communicate the true costs trucks impose. Electronic tolls are better able to charge fees based on 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. The systems vary greatly in sophistication – from complex programs providing for considerable flexibility in pricing policies to those employing simple and reliable technologies, if at the cost of flexibility.

Germany's and Austria's programs represent both ends of the spectrum, respectively, and these two cases illustrate the advantages and disadvantages of both approaches.

Germany's "Toll Collect" Truck Tolling Program

As the development of the European Union has furthered economic integration among the member nations, Germany has experienced significant growth in truck traffic, a great deal of which is comprised of foreign vehicles traveling through (May & Sumalee 2003). As the volume of goods movement traffic increased, so did concern regarding the use of public funds to maintain the quality of the road network. During the early 2000s, the German government sought the development of a system that could shift the burden of finance from taxpayers to the freight industry itself (Toll Collect 2007). In 2005, Germany launched the "Toll Collect" system, an ambitious and technologically sophisticated road pricing program for goods movement within the country. Toll Collect was primarily designed to implement direct user fees, but also to raise revenue and institute an emissions-related toll. The tolls apply to heavy goods vehicles, defined as trucks over 12 tons. The system employs on-board units equipped with GNSS receivers and digital road network maps that determine the location of the truck. As the truck drives along the highway network, the OBU keeps track of distance traveled, calculates the appropriate charges (averaging 15 cents/kilometer), and communicates this billing data to the collection agency via GSM. Various enforcement methods are employed, including DSRC communications between the OBU and roadside units. Most trucks participate in the electronic Toll Collect program although a manual payment system remains for vehicles without OBUs (Toll Collect 2007).

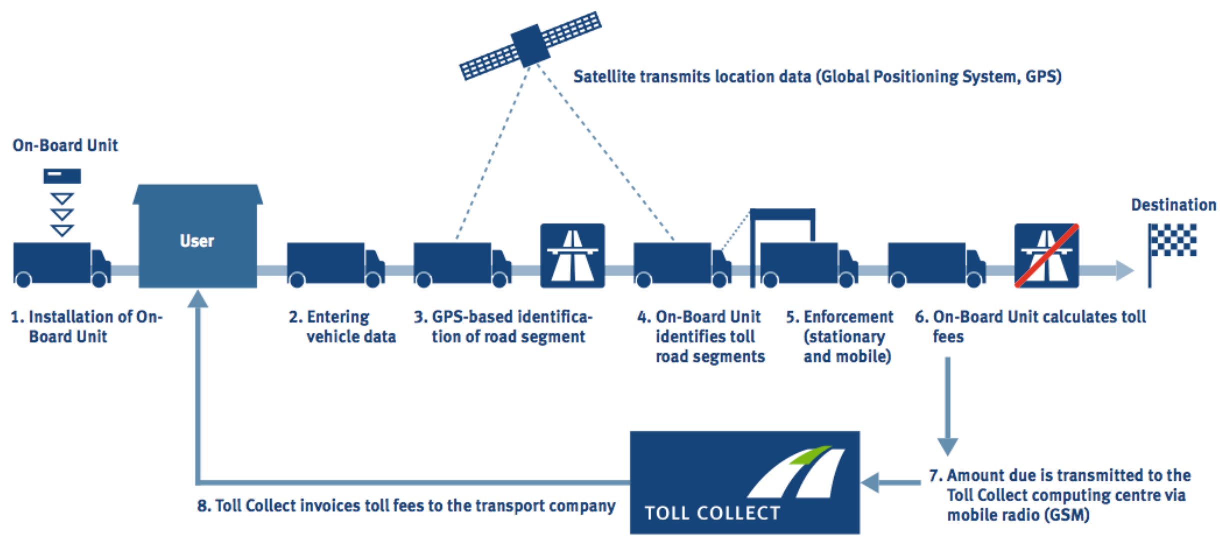

Figure 5: German Toll Collect Technological Configuration (Toll Collect 2007)

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. 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), thus encouraging lighter and cleaner vehicles via price signals (Toll Collect 2007). GNSS technology allows distance charges on a kilometer basis as well as the ability to expand the network of priced roads rather easily. The latter is particularly important since some trucks are expected to deviate from the tolled highways to other roads not desired for goods movement. Since very little roadside infrastructure is needed, the tolling program could easily begin pricing these secondary roads to discourage diversion from the highways (Bolte 2003).

Although Toll Collect is currently a successful operation, the considerable risk of implementing new technologies was exemplified by delays and budget overruns in designing a system that had never been tried before. Although the project was scheduled to start in 2003, significant problems in developing the Toll Collect system pushed the implementation date to 2005. 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). Toll income is earmarked for transportation infrastructure, most notably rail improvements in order to encourage a mode shift of goods movements. As noted earlier, the OBUs are also equipped with DSRC capability. As the rest of Europe decides between DSRC and GNSS-based systems as a common format for road tolling programs, Toll Collect's inclusion of both types ensures interoperability in the future (Ruidisch 2004).

Key Characteristics:

- OBUs store vehicle information, enabling Toll Collect to vary fees by vehicle weight and emission class
- GNSS provides ability to charge distance-based fees and to easily expand the network of priced roads
- Inclusion of the two standard types of technologies provides for interoperability with other countries' systems in the future

Goals of Pricing Policies:

- Generate revenue
- Allocate costs to users

Pros:

- System can be easily expanded over wider geographic areas

Cons:

- Using newer and less tested technologies incurred greater risk in implementation

Austria's GO Truck Tolls

Austria's electronic tolling program was launched in 2004, and is a relatively simple system relying primarily on DSRC technology. Like the Toll Collect System, the primary goal of the program is to raise revenue and charge freight vehicles for the costs they impose by traveling on Austrian highways (of particular concern is the high cost of maintaining tunnels and bridges that line the Austrian Alps) (Schwarz-Herda 2005). Participating trucks must be equipped with an in-vehicle transponder, while those vehicles without a transponder can pay tolls manually. Austria has installed a network of over 800 overhead gantries equipped with antennas throughout the highway network and 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 have enforcement cameras that take pictures of trucks that pass underneath the gantry without a valid transponder reading. From these pictures, enforcement officials use ANPR to read the license plate and identify the truck owner (Schwarz-Herda 2005).

In comparison with Germany's Toll Collect program, Austria's GO program is very simple, relying on tried and true technologies rather than experimenting with new systems altogether. Depending on a reliable technology saved Austria the delays and cost overruns that Germany experienced while implementing the Toll Collect system. However, Austria's system is rather inflexible, and while it allows for variable tolling based on vehicle size and road link, it is not easily expanded. As Sorensen (2006) explains, 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. While Germany can easily expand their tolled road network, it is impractical and expensive for Austria to install gantries on additional segments of the road network. In this sense, DSRC technology may be pushed to its limits in terms of geographical dispersion and a GNSS-based system would have been a more appropriate choice. While Germany's Toll Collect system came only after a great deal of delay and additional expense, it is likely that the benefits of a geographically flexible system will eventually outweigh these costs. Regardless, the program has been successful in raising revenue that is invested back into the road network, and Austria has been able to price their roads in a way to encourage travel on routes parallel to the Alps (Schwarz-Herda 2005).

Key Characteristics:

- Fees vary by vehicle size and road link
- DSRC gantries installed throughout the national highway system

Goals of Pricing Policies:

- Generate revenue
- Allocate costs to users

Pros:

- Using simple off-the-shelf technology ensured lower costs and faster implementation

Cons:

- System cannot be easily expanded

Distance-Based User Fees

Distance-based user fee programs that include automobiles are currently under development and have not yet seen full-scale implementation. However, there are a handful of user fee proof-of-concept experiments within the United States and results are indeed promising (Sorensen 2006). The two most thoroughly researched examples are in Oregon and at the University of Iowa. In both cases, the primary motivation is the replace dwindling gas tax revenue, although dynamic fees are also possible.

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
- 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 is equipped with an on-board unit that incudes a dashboard display, a GNSS receiver, a DSRC communicator, and an electronic feed to the odometer used to measure miles traveled. The odometer feed is the primary distance measurement tool while the GNSS receiver is used to differentiate which miles are driven in certain tolling zones, so that the appropriate fees can be levied (Whitty 2007).

The OBU also continuously keeps track of charges owed, and payments are made during the refueling process. Fueling stations are equipped with DSRC radios and communicate with the OBU automatically. DSRC was chosen over GSM for this task for its lower costs, greater reliability, and provisions for greater privacy. In the current pilot program, the distance charges are added to the cost of fuel while the state gas tax is subtracted. The driver does not need to perform any other extra tasks or pay additional bills since the mileage fee is paid during the fuel transaction. The receipt shows the separate amounts for fuel and user fees. If there is 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 is charged (Whitty 2007).

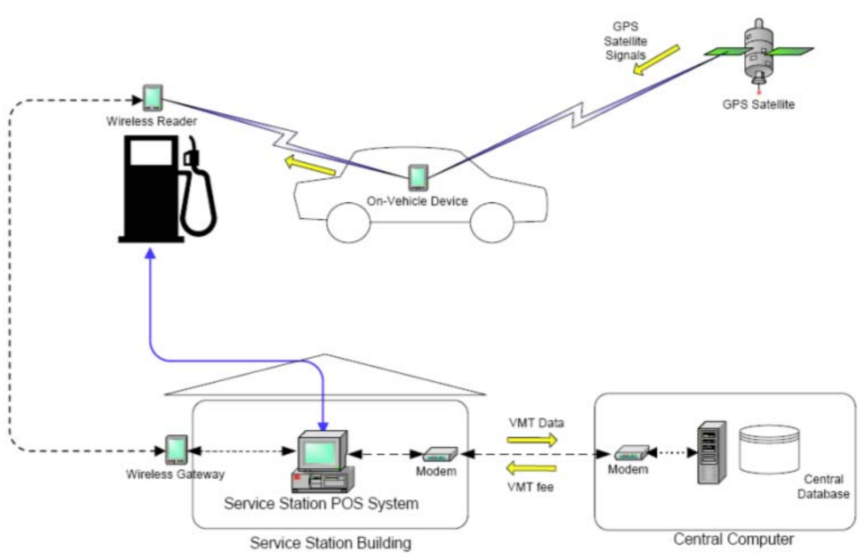

Figure 6: Oregon Mileage Fee Technical Configuration (Zhang & McCullen 2007)

From April 2006 to April 2007, the task force conducted a pilot program of the Oregon Mileage Fee Concept using nearly 300 volunteers and two service stations in Portland. In general, the program was successful and demonstrated its ability to meet the aforementioned goals of the user fee program. 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 field test participants noted that their OBU simply did not work or significantly drained the car battery, however, the researchers note that these issues were primarily due to the pilot nature of the program. Secondly, the service station operators noted some difficulty in incorporating the experimental billing equipment with their own, which would have to be streamlined in the instance of full implementation. 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. Thus, although the system operated successfully for the most part, these components need slight modifications for smoother operations in a wider implementation setting (Whitty 2007).

From a policy perspective, the pilot project demonstrated that technologies are capable of electronically determining and collecting user fees. System design can also be modified according to policy goals. Results from the pilot project 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 (although this could arguably be done to the gas tax). And lastly, 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. No agency – billing, administrative or otherwise – can link an individual to his or her travel behavior (Whitty 2007).

As Oregon's transportation revenue continues to decline, the Road User Fee Taskforce urges a statewide implementation of the user fee concept as soon as possible. Although system designers have taken many attempts to reduce the amount of equipment necessary, phasing in the required devices throughout the vehicle fleet and Oregon's fueling stations is still a significant undertaking. However, the task force estimates that with vigorous assistance from the state and federal departments of transportation, the Oregon Mileage Fee Concept could be fully operational within three to five years (Whitty 2007).

Key Characteristics:

- System can toll a statewide road network based on distance traveled
- Varying the toll based on vehicle type and emissions class is possible
- OBU calculates charges, and payment is automatically included into fuel charges
- User fee could replace the fuel tax, and attempts to tamper with the equipment results in a default fuel tax payment
- Protects privacy by delegating tasks over multiple technologies and devices

Goals of Pricing Policies:

- Generate revenue
- Develop a user-fee alternative to the fuel tax

Pros:

- Allows for charges on a wide geographic scale
- Tolls can vary by vehicle type or emissions class
- Provides for a true user fee

Cons:

- Installing equipment on the entire vehicle fleet is a challenging task

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. Like the Oregon Mileage Fee, the motivation behind a user fee charging system is primarily to replace funds from the dwindling motor fuel tax revenue. However the University of Iowa's system is being designed to operate across many states and quite possibly at the national level, so there is a greater focus on flexible charging programs allowing different rates for different jurisdictions. (Forkenbrock 2005).

An OBU in the vehicle contains a GNSS receiver, a GIS map file, a rate schedule, and an electronic odometer feed. These technologies in concert can determine a vehicle's location within a jurisdictional billing zone, and measure miles traveled to calculate total charges (Forkenbrock 2005). In addition, vehicles are equipped with a GSM transmitter that will automatically communicate 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).

Like the Oregon Mileage Fee, respecting user privacy is a paramount concern. This is accomplished 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 jurisdiction. Under this program, it will be impossible to connect which jurisdictions users have been to (Forkenbrock 2005).

Because this program was developed under an agreement between multiple states and a federal agency, the design team developed a dynamic system that can be updated with new boundaries and charging policies. This 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). According to Paul Hanley of the University of Iowa (personal communication, January 27, 2009), 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. The researchers will evaluate the system design and collect attitudinal data, and then proceed with a second testing phase with another 1,200 volunteers. Due to its flexibility and scale, the University of Iowa program holds enormous potential to change the nature of transportation finance.

Key Characteristics:

- System can toll the road network based on distance traveled and recognize different pricing policies for separate jurisdictions
- Varying the toll based on vehicle type, emissions class, time of day, particular link of the road network, and level of congestion is possible
- Protects privacy using an embedded security key
- Dynamic system with high flexibility for future needs

Goals of Pricing Policies:

- Generate revenue
- Develop a user-fee alternative to the fuel tax

Pros:

- Allows for charges on a wide geographic scale
- Tolls can vary by vehicle type, emissions class, time of day, particular link of the road network, and level of congestion
- Provides for a true user fee

Cons:

- Installing equipment on the entire vehicle fleet is a challenging task

4. Analysis

From our review of the eight cases, we observe some patterns between road pricing systems, policy goals, and technologies employed. In particular, we identified six primary policy goals:

a) maximize 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

As we have previously noted, these goals are not present in every project, and most examples tend to have two or three of these primary objectives. Another key consideration for all factors is the geographic scale at which the pricing policy is directed. Table 3 shows the relationship between pricing programs, policy goals, and technologies employed in the eight reviewed cases.

Table 3: 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	Dynamic fee to keep congestion free traffic flow											Simple; off-the-shelf technology (OST)
San Diego I-15 HOT Lanes			a, b, c	●					●			●	
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 Toll Collect			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	●	●	●	●			●		●	

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

Primary Policy Goals and Technologies Employed

As Table 3 shows, the primary policy goals for facility congestion tolls are to offer a congestion-free alternative and generate revenue. For cordon area programs, the main objective is to reduce congestion. Weight-distance truck tolls seek to generate revenue and allocate costs to users while distance-based user fee experiments have been pursued to develop a user-fee alternative to the fuel tax.

Two key factors of concern for all of these goals are the geographical scale of the pricing policy and the complexity of calculating fees to be charged. For the most part, facility and cordon area congestion tolls operate at a small geographical scale and employ simple DSRC-based systems, while weight-distance truck tolls and distance-based user fees work at a larger scale and are designed around GNSS-based systems. There are, however, a few variations of systems that cross this classification boundary.

Although the policy goals and technologies employed vary among road pricing programs, there are some aspects most systems have in common. All systems except the Singapore Congestion Toll have an explicit goal of raising revenue. Supporting information technologies such as the internet and online banking protocols play a secondary yet important role in all of the cases reviewed here, and it is difficult to imagine any electronic road pricing program that could operate without them. In addition, OBU's are found in all of the cases that employ DSRC-based or GNSS-based systems (London being the sole exception).

With regards to facility congestion tolls, the I-15 HOT Lanes and SR-91 Express Lanes show cases where the main policy goals are to offer congestion free alternatives on geographically limited facilities and to raise revenue. In these cases, simple off-the shelf DSRC-based systems proved to be effective in achieving these goals at a relatively low cost.

The two cordon pricing cases we examined, London and Singapore, have a clear policy goal in common – reducing congestion in a confined area. To accomplish this task, these road pricing programs apply a simple economic principle: the higher the price of a good, the lower the demand for the good. As long as the pricing system can charge all vehicles entering the cordoned area, congestion is reduced. The two cases in London and Singapore examined in this report show how using different technologies can determine pricing policy: Singapore's DSRC-based system has variable pricing based on congestion levels while the London system deploys only a network of cameras and ANPR technology to meter road use for a flat toll per day,

The two large-scale road pricing programs, weight-distance truck tolls and distance-based fees, share the primary policy objective of generating revenue. Weight-distance truck tolls also explicitly seek to allocate costs to users while the distance-based fee programs in the Oregon and University of Iowa examples leave a varying fee as an option. This involves 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. Because they operate at such large geographic scales and must have complex pricing structures to incorporate dynamic user fees, these systems employ advanced technologies. Most are GNSS-based, and also employ GIS and electronic odometer feeds. In these cases, policy goals direct technological specifications.

Secondary Policy Goals and Technologies Employed

In addition to geographic scale and the complexity of the pricing program, a few other policies influence system specifications and selection of technologies. The first concern is planning for future expansions of the system. While the German Toll Collect system can easily enlarge its tolled road network by simply reprogramming their GNSS-based system, Austria's DSRC-based system with on-board transponders is more difficult to expand to a large area due to the needs to install roadside gantries.

Secondly, some systems better address privacy concerns through careful system design.[8] In particular, smart cards were employed in the Singapore Congestion Toll specifically to separate billing data from personal information. In the cases of GNSS-based systems (where the possibility of tracking individuals through orbiting satellites is of high concern), privacy can be protected by dispersing personal information, vehicle attributes, and distance data across various system platforms (such as in the Oregon Mileage Fee) or by encrypting personal data (as in the University of Iowa example).

Lastly, the need for speedy implementation determines the level of complexity and advancement of technologies to employ. That is, there is clearly a tradeoff between ease of implementation and complexity of the system; the more complex the pricing policy, the more complex the system, often leading to longer development and implementation phases. Older technologies, while proven to be successfully applied in many road pricing programs, are more limited in terms of the range of policies that can be implemented. In contrast, newer and more advanced technologies have more capability of implementing various pricing options in a larger geographic area. For example, large-scale GNSS-based systems show that it will be technically feasible to incorporate facility or area-specific policies into an overarching road pricing program.

Advancements in Technology and the Changing Nature of Road Pricing Systems

As we have previously discussed, newer GNSS-based road pricing systems are enabling the implementation of large-scale dynamic user fees. We also found in the first report of this research series, "Motivations Behind Electronic Road Pricing" (Kalauskas, Taylor & Iseki 2008), that one of the most prevalent motivations behind many recent road pricing programs is the need to raise revenue. In the United States, this is driven, in part, by declining revenue from the fuel tax and jurisdictions looking to road pricing as a means to replace a primary source of transportation funds. As the geographic scale of road pricing systems with user fees increases, so does the amount of revenue generated. This has led to the design and development of large-scale GNSS-based road pricing systems such as the Oregon Mileage Fee and University of Iowa study. In this sense, policy is strongly determining the direction of technology.

Should programs like those in Oregon and the University of Iowa continue to develop as expected, it is conceivable that a well-designed GNSS-based system can essentially achieve the objectives of many road pricing programs in effect today. These programs hold great potential to flexibly implement user fees on a large scale, and represent a potential new revenue source that

[8] In this paper, we focus primarily on privacy as it relates to system design issues. The greater issue of privacy with regards to public acceptance is to be covered in greater detail in a later phase of this research.

could alleviate the crisis in transportation finance. However, since these programs rely more on in-vehicle equipment than roadside infrastructure, the primary technical challenge with these systems is to install the appropriate technology on all vehicles. A secondary technical problem is that current GNSS networks may position vehicles by as much as 15 meters away from their actual location. Thus, it would be difficult for current GNSS-based systems to differentiate between very small links in a dense urban street network. However, GNSS is still a rapidly developing technology, and it is likely that the problem of accuracy will eventually be overcome (Grush 2008).

If these two hurdles can indeed be overcome, then the necessary infrastructure will be in place for charging programs that can vary by a multitude of factors, such as road segments, time of day, vehicle class, and congestion levels. That is to say, future developments in GNSS could essentially render DSRC-based systems obsolete and most systems would be GNSS-based, employing a similar set technologies. Indeed, both London and Singapore are considering upgrading to GNSS-based systems due to advantages in geographic scale and pricing flexibility over their current systems (TfL 2006; Schindler 2007). We expect that transportation agencies wishing to implement electronic toll collection only at the facility and/or cordon level will most likely continue to employ DSRC-based systems in the short term. However, as more jurisdictions begin to see larger scale road pricing as a potent revenue generator as well as a congestion management tool that can incorporate smaller scale policies, we expect to see more regional or even statewide GNSS-based systems in the long run.

Phasing in GNSS Technology

As we have just noted, interest in GNSS-based systems is growing, but installing the necessary equipment throughout the vehicle fleet would be no easy task. How could the appropriate in-vehicle technology for a GNSS-based system be phased in? In this section we describe some of the strategies and issues that researchers and transportation agency officials have discussed on this subject.

A simple way to ensure that all vehicles will be compatible with a GNSS-based tolling system in the future 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. As the vehicle fleet turns over, the technology would slowly become ubiquitous. Based on sales and scrappage rates for automobiles and trucks, Forkenbrock (2005) roughly approximates that it would take about 20 years for 95 percent of all vehicles to have the required technology. While the cost to develop prototype equipment is high (about $400 per vehicle in the Oregon example), mass production of the units could realize significant cost reductions through economies of scale (Whitty 2007), and Sorensen (2006) estimates the additional cost for auto manufacturers to install the equipment to be on the order of $100.

While current vehicles may not have the complete set of equipment needed for a GNSS-based toll system, these technologies are nevertheless becoming more and more widespread in the transportation and communication sectors. As a result, the necessary elements of a GNSS-based toll system might already be in place, albeit not for calculating and collecting a toll. For instance, Forckenbrock and Hanley (2006) point to the proliferation of GNSS receivers (as well as the accompanying GIS map files) in vehicles for navigation purposes, and suggest that a tolling system could simply utilize these devices instead of installing a duplicate device. In addition, GSM technology is nearly universal in cellular phones, and the use of smart phones equipped with GNSS receivers is growing as well. Thus, it might be possible to utilize the capability of these devices for the purpose of tolling (Kitchen 2008). This approach might be a more cost-effective than installing similar equipment for the sole purpose of road pricing.

Indeed, this use of after-market devices instead of dedicated equipment has a precedent 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. Caltrans engineers conceived of over 100 uses for such a system, one of which is electronic toll collection. However, the very high cost of installing this infrastructure led Caltrans to pursue a demonstration project (called SafeTrip-21) that utilizes GNSS-enabled smart phones instead. Project leaders hope that the pilot project will demonstrate the benefits of VII and result in additional resources in the future (Larson 2008).[9]

However, others warn against the use of after-market devices for electronic toll collection. As Kitchen (2008) explains, such an approach might be appropriate for the purposes of navigation or providing real-time traveler information, but road pricing requires more trusted equipment. In other words, the nature of electronic toll collection demands that the primary functions (metering road use, calculating charges, and communicating data) be performed in a secure system. This is necessary to protect both the user and tolling authority from intended or unintended fraud.

Even though strategies for how to phase in the appropriate technology may differ somewhat, there is a greater consensus that whatever the strategy, it will take some time. As a result, there must be a system in place to allow those with the equipment to pay the distance-based user fee and for those without to continue paying the fuel tax (Whitty 2007; Forkenbrock & Hanley 2006; Forkenbrock 2005). For purposes of equity, many argue that the user fee should not differ greatly from the gas tax (Forkenbrock 2005). The Oregon Mileage Fee concept was designed to accommodate this transition, and Forkenbrock (2005) describes a similar system of differentiating vehicles at the pump and charging accordingly charging them user fees or gas taxes. 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.

Clearly, an explicit implementation plan does not yet exist, but this is due to the infant state of GNSS-based systems. If policy makers were to adopt such a large-scale pricing program, they would need to specify specific objectives and goals for system designers to follow.

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[9] Given the toll collection applications, the development of a VII system holds potential for the future of electronic road pricing in California as well.

5. Conclusion

In this report, we provide an overview of nine specific technologies that have been applied to electronic road pricing in recent years. These technologies have provided the necessary capability for more efficient operations for simultaneously collecting current tolls and enabling new pricing policies. In the cases examined in this report, we observed that policy decisions regarding the size of the network to be tolled and the complexity of the charging program drove the system design of each electronic toll collection system. While each system is different, most systems can generally be categorized by the primary technology employed to implement meter road use, that is, DSRC, GNSS, or ANPR. We also identified six primary policy goals of road pricing systems:

a) Maximize 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

All of the cases we examined had a primary policy goal of generating revenue, except for the Singapore Congestion Toll.

Facility congestion toll programs have the primary goals of raising revenue and offering a congestion-free alternative while cordon congestion tolls aim to reduce overall congestion. To accomplish this, a road pricing system needs to charge users as they enter an individual facility or a defined area. DSRC-based systems generally work best at these small geographical scales, and can be quickly deployed at a low cost; building overhead gantries and antennas is easy to do in a small area, and on-board transponders are inexpensive and easily installed. As demonstrated by the I-15 HOT lanes and Singapore's congestion charge, these systems provide for significant flexibility in charging programs as well.

However, as the geographic scale of the tolled road network increase, DSRC-based systems become less practical due to the need to build roadside gantries on a large scale. These road pricing programs, weight-distance truck tolls and distance-based user fees, also have the common policy goals of raising revenue and distributing the full cost of road use to the driver. The latter may involve measuring a variety of factors such as distance traveled, time of day, vehicle class, and congestion levels. Because of the large geographic scale and complexity of the fee to be charged, GNSS-based systems are better suited to these applications.

We have noted that GNSS technology is a new technology, and that GNSS-based systems currently take longer to implement. However, as interest in large-scale GNSS-based road pricing programs grows among policymakers, they will become a more proven and more easily implemented technology. One current limitation is that GNSS that may be off by as much as 15 meters in its positioning, and needs backup technologies for more accurate measurements. However, new developments in this technology may fix this problem, making GNSS-based systems the logical choice for most road pricing projects in the future.

An underlying concern in many cases examined here is the issue of privacy. In particular, London's congestion toll may be especially unpopular among users because it relies on a network of cameras spread throughout the city and the centralization of user data. But in all examples where privacy was of particular consideration, system designers have been able to take appropriate steps to protect personal information. In London's case, the vehicle images are promptly deleted and in Singapore, user data and billing information are kept on a smart card belonging to the driver. In GNSS-based systems, satellites send one-way communications to OBU's, so that vehicles are never tracked. In the Oregon example, usage and billing data are diffused over different components and the University of Iowa's system uses an encryption key. In all cases, privacy is protected through careful system design. While it is uncertain if it is possible to lose the "Big Brother" association altogether, the public should nevertheless be assured that electronic road pricing systems are designed in such a way that travel behavior data cannot be linked to personal information without prior consent.

All of the fully operational electronic toll collection programs examined in this report have been successful in fulfilling their primary objectives, although some systems address secondary concerns more efficiently. In addition, experiments of domestic GNSS-based systems that seek to replace the gas tax are promising, and there are a handful of feasible strategies for phasing in the necessary equipment. In general, the sentiment is that technical feasibility is no longer a problem in facilitating the policy goals for road pricing programs. That is, road pricing's limiting factor is no longer technology, but rather political and public support for implementation.

References

Balmer, U. (2004). The window of opportunity: How the obstacles to the introduction of the Swiss heavy goods vehicle fee (HVF) have been overcome. In *Managing Transport Demand through User Charges: Experience to Date*. International Conference Hosted by Transport for London, Jan. 23, 2004, London. Retrieved 22 May 2008 from http://www.internationaltransportforum.org/europe/ecmt/taxes/pdf/London04Balmer.pdf.

Boarnet, M. & Dimento, J. (2004). The Private Sector's Role in Highway Finance: Lessons From SR-91. *Access*, 25, 26-31.

Bolte, F. (2003). Fee collection for heavy goods vehicles on German motorways. BASt Presentation IEE Seminar "Road User Charging" London March 11, 2003.

Brownstone, D., Ghosh, A., Golob, T.F., Kaximi, C. & Van Amelsfort, D. (2003). Drivers' Willingness-to-pay to Reduce Travel Time: Evidence From the San Diego I-15 Congestion Pricing Project. *Transportation Research Part A: Policy and Practice,* 34(4), 373-387.

Commission for Integrated Transport. (2006). *Road Charging Scheme: North America - USA, California: Interstate 15, San Diego.* Retrieved 17 May 2008 from http://www.cfit.gov.uk/map/northamerica-usa-california-sandiego.htm.

ESA. (2007). What is Galileo? Retrieved 6 June 2008 from http://www.esa.int/esaNA/GGGMX650NDC_galileo_0.html.

EPVIS. (2002). Electronic Parking System. Retrieved 21 May 2008 from http://www.epvis.com.sg/EPV_CarPark.htm.

FHWA. (2003). *A Guide for HOT Lane Development*. Washington D.C.: Federal Highway Administration.

Forckenbrock, D. & Hanley, P. (2006). Mileage-Based Road User Charges. *Public Roads*, 69(5).

Forkenbrock, D.J. (2005). Implementing a Mileage-Based Road User Charge. *Public Works Management & Policy*, 10(2): 87-100.

Goh, M. (2002). Congestion Management and Electronic Pricing in Singapore. *Journal of Transport Geography*, 10(1): 29-38.

Grush, B. (2008). Road Tolling Isn't Navigation. *European Journal of Navigation*. Retrieved 12 July 2008 from www.skymetercorp.com/cms/images/ news/RoadTollingIsNotNavigation.pdf.

Kalauskas, R., Taylor, B.D., & Iseki, H. (2008) Under review. Motivations Behind Electronic Road Pricing: What is the Driving Force Behind the Worldwide Rise in

Tolling? A Review of Innovative Road Pricing from Across the Globe. 72 pages, California PATH Research Report, California PATH Program, Institute of Transportation Studies, University of California, Berkeley.

Kitchen, M. (2008, April). Traffic Choices Study: Findings From a Road Pricing Experiment. *Transportation Seminar Series.* Lecture given at the Portland State University Transportation Seminar, Portland, Oregon.

Kuhl, J. (2007). Project Overview: National Evaluation of a Mileage-Based Road User Charge. Retrieved 31 May 2008 from http://ppc.uiowa.edu/dnn4/TransportationbrPolicyResearch/RoadUserChargeStudy/tabid/65/Default.aspx.

Larson, G. (2008). Intelligent Vehicles and Roads: The VII Program and the SafeTrip-21 Initiative. Presentation given at *The 18th Annual Symposium on the Transportation, Land Use, and Environment Connection: The Future of Cities and Travel.* Conference hosted by the UCLA Extension Public Policy Program, October 20, 2008, Lake Arrowhead, CA. Retrieved 19 December 2008 from http://www.uclaextension.edu/arrowhead/ppts_09/A9.ppt.

Litman, T. (2006). London Congestion Pricing: Implications for Other Cities. Victoria: Victoria Transport Policy Institute.

May, A. D. & Sumalee, A. (2003). One Step Forward, Two Steps Back?: An Overview of Road Pricing Applications and Research Outside the United States. *International Persepectives on Road Pricing* (pp. 73-88). Key Biscayne, Florida: Transportation Research Board.

Network for Electronic Transfers. (2007). NETS CashCard. Retrieved 21 May 2008 from http://www.nets.com.sg/consumers/netscashcard/ncc_about_use.php.

OCTA. (2007). 91 Express Lanes. Retrieved 18 May 2008 from http://www.91expresslanes.com.

Poole, R. (2007, November 8). Life in the Slow Lane. *ReasonOnline*.

Redcorn Ltd. (2008). ANPR. Retrieved 1 June 2008 from http://www.redcorn.co.uk/index.php?option=com_content&task=view&id=14&Itemid=31.

Redhaus Industrial Design and Control. Automatic Number Plate Recognition. Retrieved 19 May 2008 from http://www.rednaus.com/ANPR.html.

Ruidisch, P. (2004). The German Truck Charge. In *Managing Transport Demand through User Charges: Experience to Date*. International Conference Hosted by Transport for London, Jan. 23, 2004, London. Retrieved 22 May 2008 from http://www.internationaltransportforum.org/europe/ecmt/taxes/pdf/London04Ruidisch.pdf.

SANDAG. (2007). About FasTrak. Retrieved 17 May 2008 from http://www.sandag.cog.ca.us/index.asp?classid=29&fuseaction=home.classhome

SANDAG. (2006). *Task 3.1: I-15 Managed Lane Electronic Toll Collection System (ETCS) Concept of Operations.*

Schwarz-Herda, F. (2005). Toll Collection in Austria: Implementation of a fully electronic system on the existing motorway network. *PIARC Seminar on Road Pricing with emphasis on Financing , Regulation and Equity.* Cancun, Mexico.

Schindler, N. (2007). Siemens References in Electronic Tolling. Retrieved 12 July 2008 from http://fp.is.siemens.de/traffic/EN/pdf/products/tolling/speeches/SiemensReferences.pdf.

Small, K. (2005). Unnoticed Lessons From London: Road Pricing and Public Transit. *Access*, 26, 10-15.

Sorensen, P.A. (2006). *Review and Synthesis of Innovative Electronic Tolling Applications Worldwide.* Los Angeles: UCLA Institute of Transportation Studies.

Sorensen, P.A. & Taylor, B.D. (2006). Innovations in Road Finance: Examining the Growth in Electronic Tolling. *Public Works Management & Policy*, 11(2): 110-125.

TfL. (2006). *Distance Based Charging: Report on Transport for London's GPS OBU Trial.* Retrieved 12 July 2008 from http://www.tfl.gov.uk/assets/downloads/GPS-OBU-trials.pdf.

TfL. (2007a). *What Do I Need to Know About the Central London Congestion Charge Camera System?.* Retrieved 20 May 2008 from http://www.tfl.gov.uk/assets/downloads/CC-Cameras.pdf.

TfL. (2007b). *Central London Congestion Scheme: Impacts Monitoring*.

TfL. (2008). Congestion Charging – Transport for London. Retrieved 20 May 2008 from http://www.tfl.gov.uk/roadusers/congestioncharging/default.aspx.

Toll Collect. (2007). *Truck Toll in Germany: User Information.* Retrieved 24 January 2009 from http://www.toll-collect.de/pdf/benutzerinformation/web_einfuhrungstex_gb.pdf.

TransNet. (2008). Keep San Diego Moving: I-15 Corridor. Retrieved 13 January 2009 from http://keepsandiegomoving.com/CW_Images/I-15InfoGraphic.wmv.

Samuel, P. (2004, October 4). German Gov sues Toll Collect for $4.3b in satellite toll failure. *TollRoadsNews*. Retrieved 22 May 2008 from http://tollroadsnews.info/artman/publish/article_670.shtml.

Turner, D. (2003). Central London's Congestion Charging Scheme: Has It Achieved Its Objective? *International Persepectives on Road Pricing* (pp. 17). Key Biscayne, Florida: Transportation Research Board.

University of Iowa Public Policy Center. (2008). University of Iowa Public Policy Center's Road User Study: Background Information. Retrieved 22 January 2009 from http://roaduserstudy.org/media.aspx.

VTA. (2005). *Final Report: Santa Clara County HOT Lane Feasibility Study*.

Wachs, M. (2003). Then and Now: The Evaluation of Congestion Pricing in Transportation and Where We Stand Today. *International Perspectives on Road Pricing* (pp. 63-72). Key Biscayne, Florida: Transportation Research Board.

Wachs, M. (2006). *A Quiet Crisis in Transportaiton Finance: Options for Texas.* RAND Corportation.

Werder, H. (2004). Impact of the heavy vehicle fee: Central pillar of the Swiss transport policy. In *Managing Transport Demand through User Charges: Experience to Date*. International Conference Hosted by Transport for London, Jan. 23, 2004, London. Retrieved 22 May 2008 from http://www.internationaltransportforum.org/europe/ecmt/taxes/pdf/London04Werder.pdf.

Whitty, J. M. (2007). *Oregon's Mileage Fee Concept and Road User Fee Pilot Program.* Oregon Department of Transportation.

Worrall, H. (2003). Technology and Pricing: Cause or Effect? *International Perspectives on Road Pricing* (pp. 37-38). Key Biscayne, Florida: Transportation Research Board.

Zhang, L. & McCullen, B.S. (2007). Statewide Distance-Based User Charge: The Case of Oregon. *TRB 2008 Annual Meeting CD-ROM*.