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Congestion pricing applications to manage high temporal demand for public services and their relevance to air space management

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ABSTRACT

This paper surveys pricing mechanisms used by government agencies to manage congestion, as well as highlights the many political and social issues that have to be addressed in order to implement a pricing mechanism. This survey was undertaken in order to be able to understand how congestion pricing could be used to help manage airspace capacity. This is an important question since a 2008 analysis by the Joint Economic Committee of the US Congress suggested that domestic air traffic delays in 2007 cost the economy as much as $41 billion, including $19 billion in increased operational costs for the airlines and $12 billion worth of lost time for passengers.

The paper begins by surveying roadway congestion approaches throughout the world. We survey the successes that peak pricing charges have had on reducing congestion. We also report the other benefits that such practices have had: improving the public transportation network, improving the economy of the region, reducing carbon emissions, and creating new urban living spaces. We next examine other applications of congestion pricing, including managing demand for canal and bridges passage, port usage, access to city centers, and peak use of energy resources.

The paper ends with a proposal for a two-staged approach to the management of air space and runway congestion. The first stage imposes a service standard on runway access that is consistent with an airport's capacity during good weather days. Then, when weather reduces capacity either in the airspace or on runways, we propose a congestion pricing mechanism that charges flights based on the amount of congestion the flight imposes on the entire system.

1. Introduction

Congestion occurs when demand is greater than supply and when there is little or no restriction on who can use the demanded asset. Often, the problem leads to what is known as the "Tragedy of the Commons" a concept as old as Aristotle, who noted: "what is common to the greatest number has the least care bestowed upon it." In such cases, each agent acts in his own self-interest and uses the asset as if it were inexhaustible. Even when people understand that the asset is scarce and that overuse can harm everyone, it is still in one's own best interest to act without restraint unless there is a collective agreement that imposes restrictions on all. Thus, congestion is caused by the lack of a mechanism to efficiently manage the use of the capacity and government regulation is necessary to determine the allocation and use of scarce goods.

The US Department of Transportation reports: "Growing congestion in the US transportation network poses a substantial threat to the US economy and to the quality of life of millions of Americans." According to the 2009 Texas Transportation Institute (TTI), the congestion "invoice" for the cost of extra time and fuel in 439 urban areas in 2007 was $87.2 billion as compared with $63.1 billion in 2000 and $16.7 billion in 1982 (all in constant 2007 dollars). [UTCM Report, 2009]. The same report concludes that congestion wasted 2.8 billion gallons of fuel and 4.2 billion hours of extra time. They estimate that free flowing traffic is seen less than one-third of the time in urban areas with over 1 million people. They also estimate that delays have grown five times larger overall since 1982. They conclude that the $87.2 billion cost in 2007 would be substantially higher (perhaps almost triple the estimate) if it accounted for the significant cost of system unreliability and unpredictability, the environmental impact of idle-related auto emissions, and higher gasoline prices. These delays cause the average peak-period traveler to spend an extra

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36 h of travel time and use 24 gallons of fuel consumption which amounts to a cost of $760 per traveler in 2007. They conclude that small traffic volume declines brought on by increases in fuel prices over the last half of 2007 caused a small reduction from 2006 to 2007.

Congestion pricing is one approach that the government can use to alleviate some types of congestion. Again according to the US Dept of Transportation (2006):

> "Congestion pricing—sometimes called value pricing—is a way of harnessing the power of the market to reduce the waste associated with traffic congestion. Congestion pricing works by shifting purely discretionary rush hour highway travel to other transportation modes or to off-peak periods, taking advantage of the fact that the majority of rush hour drivers on a typical urban highway are not commuters. By removing a fraction (even as small as 5%) of the vehicles from a congested roadway, pricing enables the system to flow much more efficiently, allowing more cars to move through the same physical space. Similar variable charges have been successfully utilized in other industries—for example, airline tickets, cell phone rates, and electricity rates. There is a consensus among economists that congestion pricing represents the single most viable and sustainable approach to reducing traffic congestion. Although drivers unfamiliar with the concept initially have questions and concerns, surveys show that drivers more experienced with congestion pricing support it because it offers them a reliable trip time, which is very valuable especially when they have to be somewhere on time. Transit and ridesharing advocates appreciate the ability of congestion pricing to generate both funding and incentives to make transit and ridesharing more attractive."

In this paper we present applications of congestion pricing throughout the world. We find that the most common application is in managing road congestion but we also highlight other applications such as peak charges for access to canals, bridges, and city centers, as well as its use by electrical and water utility companies.

The purpose of this paper is to provide an overview of how pricing mechanisms have helped to manage congestion, as well as highlight the many issues that have historically occurred in implementing such mechanisms. Our ultimate goal is to determine if congestion pricing or some other market-clearing mechanism can assist in the management of congested airspace. We provide some examples as to how congestion pricing might be imposed on the airspace.

We begin our presentation by providing a brief history of congestion pricing as it has been applied to highways use and for access to cities through bridges (often labeled "cordon pricing").

2. Transportation pricing

When thinking about how to alleviate road congestion, most individuals immediately think of adding a new lane to an overburdened highway or bridge. However, the costs of such construction are enormous and usually the highest—because of land values—in the most needed locations. The approval and eventual building of these facilities can often take decades. And, adding such lanes might even increase congestion. This phenomenon is known as Braess's paradox (1969). This paradox shows that, even for very simple networks, a Nash equilibrium can result in longer travel times when individuals choose the path most beneficial to themselves. The Wikipedia article on Braess's paradox provides a simple example and a number of references. It also provides corollaries to this paradox that show instances where *removing* a portion of the network can *improve* traffic flow (e.g. in Korea, Stuttgart, and New York City). For a more theoretical view of Braess's paradox and its application to road networks, see Roughgarden (2006).

Taxes collected for road construction are usually from three major sources: weight-based taxes for commercial vehicles, per-gallon gasoline and diesel taxes, and tolls collected on major highways. Weight-based taxes are assessed to the heaviest vehicles since these trucks and buses do the greatest damage to the road surfaces and are collected to partially pay for the repairs of these roads. The per-gallon taxes go into a general fund and there is no mechanism for the gasoline tax to differentiate between gasoline use on unimpeded roads and the fuel burned on congested roadways. Often, even on toll roads, the fees collected are set so as to recover the construction and normal operating costs. Thus, the three major sources of funds are insufficient to pay for new road or bridge construction to accommodate the massive growth in highway use in most urban regions. The fees and taxes that most motorists pay do not cover the costs of congestion and thus, motorists are not paying the true costs incurred. Overuse is inevitable and the funds collected are often not used where most needed.

The idea of road pricing is not new. French civil engineer, Jules Dupuit in an article published in 1844 argued that one should determine the optimum toll for a bridge based on *marginal utility*. Arthur Pigou (1920) furthered this concept by making the distinction between private and social marginal products and costs. He originated the idea of externalities, i.e., costs imposed or benefits conferred on others that are not taken into account by the person taking the action. He argued that the existence of externalities is sufficient justification for government intervention. He proposed that the government should impose taxes on negative externalities (e.g., overuse of public services) and should reward positive externalities (e.g., the government should provide support to education because individuals do not necessarily see the societal benefits of such investments). Frank Knight (1924) argued that privately owned, competitive roads would result in their optimal use and optimal investment since market forces would provide the pricing signals necessary for optimal use.

William Vickrey, winner of the Nobel Prize for Economics in 1996 proposed, in 1951, that subway systems and road networks impose fares that increase in peak times and in high-traffic areas (Vickrey, 1955). He argued that time-of-day pricing could better balance supply and demand. Such pricing would encourage the use of alternative modes of transportation, such as car pools and public transportation. It could also increase the throughput on the tolled highways since congestion reduces the overall throughput. Vickrey argued that congestion pricing allocates the scarce resource based on an efficiency principle—the goods are allocated to those that value them the most. In addition, pricing plays two other important purposes: It provides information about the areas that require capacity expansion the most and it provides resources for such expansion.

We summarize below some of the economic considerations one should keep in mind when considering congestion management approaches. For a more complete description of the economic underpinnings, we suggest the papers by Button (2004,2005).

1. The determination of a traffic-flow target should be determined externally and unrelated to how that capacity is allocated. Once a goal is set, congestion pricing will determine the prices that meet or come close to meeting that target. There can be many social and policy issues that come into play when setting this target. There must be a balance between an underutilized roadway and one where flow is significantly impeded. The road may be used for other purposes that may

mitigate a perfect throughput target. Button and Vega (2007) point out that congestion may not be the only measure of best use. Within the road context, the target is likely to be determined based on throughput considerations, high-occupancy vehicle demands, public transportation availability, emissions issues, and other public concerns. Once this target is set, pricing can then be used to match the flow to this target.

2. When setting prices, one should consider the marginal social cost of each trip. Simply put, the act of a single vehicle joining the traffic stream may have little impact on congestion when there is excess capacity, but may add significantly to the buildup as traffic mounts. Thus, the price should signal to the user the impact that the user has on others. One can think of road pricing as being similar to a private company's pricing policy. A company calculates its production schedule and likely demand for the product. It sets the price accordingly. If the company finds that demand is higher than anticipated, prices are increased. On the other hand, if demand is lower than expected, prices decrease. Congestion pricing should act in a similar manner. When there is significant congestion, the price is increased and only as congestion abates does the price decline. When sufficient funds have amassed to allow new construction, the new capacity will be reflected in revised congestion prices.
3. The congestion price cannot be determined solely by conditions at the time of the individual trip since queues build overtime and must abate. Thus, the price should take into account the impact of the trip on other traffic from the time the trip is made until the end of the congestion period. Thus, one must consider the impact that trips have on future periods.
4. An externality is an effect of a purchase or use decision by one set of parties on others who did not have a choice and whose interests were not taken into account in terms of the cost of the purchase. Thus, externalities often shift some of the costs from the purchaser or user of the good to other unrelated third parties. An externality can be either positive or negative. There is a collection of externalities that are often not considered when evaluating the costs of building of new roads, or the costs of congestion on existing roads. Specifically, one often does not consider the loss to the economy of commuting time or of environmental costs when thinking about congestion costs. A single accident in one location can cause traffic tie-ups on the highway in the lanes going in the opposite direction or on traffic many miles away from the accident. Just as negative externalities are often not considered, positive implications are often overlooked when performing cost/benefit analysis for road construction or public transit expansion. For example, improving traffic flow in one part of the network can improve flow in other locations. Imposing congestion pricing and simultaneously improving public transportation can improve the environment, improve the overall economic condition of the region, and encourage new business to an area.
5. For dynamic pricing to work well, charges should vary smoothly over time. If one is using a price signal to move travelers from peak to non-peak, then by shifting the prices smoothly over time one does not create incentives for a mass movement to enter a highway a few minutes prior to a price increase and thereby move the surge in demand to another time period.

Keeping these principles in mind, we now provide some examples of highway pricing and urban road pricing. This discussion will highlight both the positive and negative impacts of these price policies and the necessary political and social efforts necessary to implement the policies that are currently in place.

2.1. Congestion pricing on roadways

Vehicle "throughput" on a freeway is the number of vehicles that traverse that road over a given period, such as an hour. Once freeway traffic exceeds a certain threshold level, both vehicle speed and vehicle throughput drop precipitously. Data show that maximum vehicle throughput occurs at free flow speeds ranging from 45 mph to 65 mph, depending on the configuration of the road. The number of vehicles that pass through an area per hour can drop by as much as 50% when severe congestion sets in. At high traffic levels, the freeway is kept in this condition of "collapse" for several hours after the rush of commuters has stopped. This causes further unnecessary delay for off-peak motorists who arrive after rush hour.

With peak-period highway pricing, a variable toll dissuades some motorists from entering freeways at those access points when traffic demand is high or where surges in demand may push the freeway over some critical threshold.

We present tolling approaches to manage demand. Such tolling may be set in advance by time of day, based on traffic volumes observed (during the past week, month, or quarter) or they may be dynamically set by observation of the existing traffic. We divide our examples into (a) variable tolling on an entire roadway or bridge, (b) variable tolling on specific lanes of a highway, and (c) cordon charges whereby the vehicle is charged either a variable or a fixed charge to drive within or into a congested area of a city.

2.1.1. Examples of variable tolls on entire roadways

2.1.1.1. NJ Turnpike. The New Jersey Turnpike is an example of a variable toll highway. It is the most heavily traveled roadway in the country with average daily trips exceeding 500,000. The variable pricing began in the fall of 2000 with 7% higher tolls during peak traffic hours than during non-peak hours. This pricing change resulted in a 14% decrease in peak morning traffic and an equivalent decrease in evening traffic. However, the prices are fixed throughout the year and there are many times, especially in summer months, where the tolls are insufficient to reduce demand to match capacity.

2.1.1.2. Port Authority interstate vehicle crossings. The Port Authority of New York and New Jersey adopted a variable toll strategy for users of electronic toll collection in 2001. The Port Authority gives a 20% discount for off-peak tolls on its bridges and tunnels relative to peak periods. There are three rates for EZ-Pass passengers: off peak, peak, and truck off-peak weekday-overnight. Peak periods are 6–9 a.m. and 4–7 p.m. Monday–Friday, and noon–8 p.m. on Saturdays and Sundays. All other times are off-peak. In addition, there is a Port Authority Green Pass Discount Plan which offers a special $4.00 toll rate to vehicles certified to the California Super-Ultra-Low Emission Vehicle (SULEV) standard and achieves a United States Environmental Protection Agency (USEPA) highway fuel economy rating of 45 miles per gallon or more. Thus, tolls are being used to both manage congestion and to accommodate emissions reductions. Similar to the NJ Turnpike tolls, the prices are not dynamically set. There are many periods where the traffic is much greater than the capacity of the system.

2.1.1.3. Other examples. Other highways using variable pricing in the US include Cape Coral and Midpoint Bridges in Lee County, Florida, The Sawgrass Expressway and the Tappan Zee Bridge over the Hudson River, I-394 MnPASS in Minnesota, US 36 and the extensions in Pecos and I-25 north of US 36 in the Denver/Boulder area of Colorado, I-15 Express Lane Pilot Project in Salt Lake, Utah, Dulles Greenway (Virginia), and route SR167 in Seattle, Washington.

2.1.1.4. Highways studying variable pricing. There are currently a variety of highways authorities studying whether to transform their pricing to one that varies prices for peak periods. They include I-90 Northwest Tollway in Chicago, Illinois and The Pennsylvania Turnpike, and GA-400 in Georgia.

2.1.2. Examples of variably priced lanes

High Occupancy Toll (HOT) lanes are limited-access, and usually barrier-separated, highway lanes that provide free or reduced cost access to qualifying HOVs. They also provide access to vehicles that are willing to pay a charge and do not meet passenger occupancy requirements. For these paying vehicles, the price is set dynamically based on existing traffic and travel conditions. Communication is usually via variable message signs that post the current price. Potential users decide whether to use the HOT lanes or the parallel non-tolled lanes. The information presented below is a summary of information provided by the US Department of Transportation, Federal Highway Administration Web Pages.

2.1.2.1. State route 91 (SR 91) Express Lanes—Orange County, California. California's SR 91 Express Lanes provide two lanes in each direction between the SR 91/55 junction in Anaheim and the Orange/Riverside County Line. The lanes run for approximately 10 miles in the median of SR 91. Access points to the Express Lanes are provided only at each end of the facility. The availability of publicly owned right-of-way in this super congested corridor played a large role in the facility's creation and made it possible to provide two travel lanes in each direction.

Launched in December 1995, the facility was a pioneer application of variable pricing in the US, and was funded through private investments. When planning for the toll lanes began, the need for improvements in the highly congested SR 91 corridor had been evident for many years. Public funding was unavailable and was unlikely to materialize in the next 10 years. California legislation AB 680, allowed California Department of Transportation (Caltrans) to enter into agreements with private entities for the construction by private entities of four transportation demonstration projects, including at least one in Northern California and one in Southern California. The legislation authorized Caltrans to lease rights-of-way, grant easements, and issue permits to enable private entities to construct transportation facilities supplementing existing state-owned transportation facilities. The law also allowed Caltrans to lease those facilities to the private entities for up to 35 years.

The SR 91 corridor in which the Lanes are situated is one of the most heavily traveled routes in Orange County, California, and one of the most highly congested freeway corridors in California. On a typical day, roughly 250,000 vehicles use the route, and before the 91 Express Lanes opened, peak period delays often ranged between 20 and 40 min. The $134 million SR 91 Express Lanes facility was one of the four public–private partnerships made possible by AB 680. To use these expressways, drivers must possess an electronic transponder. Carpools with 3 or more passengers may also use the facility at a 50% discount. In addition, zero emission vehicles, motorcycles, and vehicles with disability or veteran license plates also have access to these lanes. When first created, a single toll applied for the entirety of the peak periods. However, in September 1997, tolls were adjusted hour by hour during the morning and evening rush hours. The facility uses a simple tolling system, with all vehicles using the same entry and exit points. Tolls vary only by time of day and not by the length of trip on the facility, as all trips are of the same length. As of April 1, 2010, the highest toll charged was $10.25 which was applied only on Fridays from 3:00 to 3:30 pm eastbound. Only during the evening hour rush hour did tolls increase above $5.00. All other times the eastbound tolls were between $1.30 and $3.50. Similarly, in the westbound morning rush hour tolls could be as high as $4.25 and during non-rush hours were between $1.30 and $3.00. Weekday two-way traffic on the SR 91 Express Lanes has averaged roughly between 25,000 and 35,000 vehicles, indicating that only a small portion of SR 91 Express-Lane-registered users actually use these lanes on a given weekday. These lanes average 60–65 miles per hour (mph) during the peak rush hour.

Lessons learned from pricing the I-91 experience include the following:

1. One of the most important selling factors of HOT lanes to users is the reliability of traffic conditions in the Express Lanes. Users value the security that they are unlikely to experience congestion and that any traffic incidents will be addressed quickly and cleared.
2. A number of institutional issues were observed during the construction and management of this toll roll. First, operating a HOT facility with private funds created a perceived conflict of interest problem that has resulted in the state moving to acquire the toll lanes. Secondly, the acceptance of the project has been difficult because of both private ownership issues and the newness of the express lane concept. Thirdly, the project required multiple changes to the tolling structure over time. Specifically, as demand for the facility changed, the HOV2+carpools that had initially traveled for free, were required to pay 50% of the normal toll and the amount of the toll has been adjusted several times since its opening. Finally, the success of the SR 91 Express Lanes depends on the congestion in the general-purpose lanes. The tolls in the HOT lanes must be set so that those paying for Express Lane service will be traveling at highway speeds. This is possible only when one has the ability to dynamically set the tolls.

2.1.2.2. I-15 San Diego. In 1996, the San Diego Association of Governments (SANDAG) installed managed lanes, now called "HOT" lanes on Interstate 15 (San Diego) when it was determined that only 30–50% of the capacity of the HOV lanes were being used. The HOT lanes allow high-occupancy vehicles to use the lanes for free but charge others to use these lanes. Initially, the lanes were operated with monthly permits for unlimited use. In 1998, electronic tolls replaced the decal system and allowed for per-trip pricing that was variable for peak pricing. "Intelligent Transportation Systems" (ITS) technology is used to constantly measure traffic flow and the number of vehicles traveling on the road. The toll rates go up when traffic is high and decrease as traffic ebbs.

On normal commuting days, the tolls range from $0.50 to $4.00 depending on current traffic conditions; however, tolls may be raised up to $8.00 in the event of severe traffic congestion. Electronic signs at the entrance to the HOT lanes notify motorists of the current toll as they approach the toll lanes. Motorists enter the HOT lanes at normal highway speeds. The dynamic pricing system insures that cars move at no lower than 55 mph thereby assuring that buses using these lanes are encumbered. The toll revenue collected is used to increase the express bus service. To preserve the carpooling incentives, vehicles with two or more occupants may always use the *FasTrak* lanes for free. The lanes operate only during peak hours in the direction of the commute. From 5:30 a.m. to 11 a.m., all vehicles in the HOT lanes travel southbound; from 11:30 a.m. to 7:30 p.m., all vehicles travel northbound.

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Given the growth in vehicles using I-15 over the last decade and the success of the *FasTrak* HOT lanes on the highway, the HOV lanes have been expanded, resulting in a total of 20 miles of four lanes (80 lane-miles) with a movable barrier.

The expansion extends the I-15 HOT lanes north as far as SR 78 in Escondido and creates a 20-mile, two-directional managed lane facility. The lanes use advanced technologies to monitor traffic service on the road, detect problems, and keep vehicles moving. The lane configuration changes to accommodate peak directions traffic to use the express lanes and provides multiple entry and exit points to the lanes. An 800-person telephone survey of I-15 users conducted in fall 2001 indicates that the majority of motorists support the lanes, and that motorists with the most extensive experience with the *FasTrak* lanes are the most ardent supporters.

An 800-person telephone survey of I-15 Express Lane users completed in the summer and fall of 2001 demonstrates that motorists of all income levels recognize the benefits of HOT lanes. Specifically:

- 91% of those surveyed think that travel time savings options provided by the I-15 Express Lanes are a "good idea",
- 66% of drivers who do not use them support the I-15 Express Lanes,
- 73% of non-HOT lane users agree that the HOT lane reduces congestion in the corridor,
- 89% of I-15 users support the extension of the Express Lanes,
- The extension of the Express Lanes was the top choice of both HOT lane users and non-users for reducing congestion in the corridor and 80% of the lowest income motorists using the I-15 corridor agreed with the statement that "People who drive alone should be able to use the I-15 Express Lanes for a fee." Despite equity concerns that have been raised in locations without HOT lanes, low-income users in San Diego were more likely to support the statement than the highest income users.

2.1.2.3. Katy Freeway QuickRide and US 290 QuickRide (Houston, Texas). Houston's IH 10 corridor, known commonly as the Katy Freeway, extends 40 miles from the Central Business District of Houston west to the Brazos River. It was constructed from 1960 to 1968 to replace the old Katy Road, when Houston was a much smaller city. Since its construction, explosive growths in private residences, corporate offices, and retail centers along the route have made the IH-10 corridor a central artery of western Houston.

Designed to carry 79,200 vehicles per day, the Katy Freeway carried over 207,000 vehicles per day in 2009, and it is considered one of the most congested stretches of freeway in Texas. The Katy Freeway also has the highest daily truck volumes of any roadway in the state. Congestion may be present for 11 h or more each day, extending well beyond conventional peak hours, and, even on weekends, there can be long periods of congestion. Some advocates for new road construction estimate the cost of the Katy Freeway's traffic delays to commuters, residents, and businesses at $85 million a year.

The Katy Freeway originally had three main lanes (or general purpose lanes) and two frontage-road lanes for most of its length in each direction. In 1988, a barrier-separated high-occupancy-vehicle/toll (HOV) lane for carpools and buses was built. This single reversible HOV lane handled inbound traffic in the morning and outbound traffic in the evening. In 1998, the HOV lane was converted to a HOT lane in which HOV-3 vehicles and buses could use the lane at no cost and which HOV-2 vehicles could use for a fee of $2.00. This single HOV-3 lane was replaced with four HOT lanes in the median of a widened freeway, two in each direction, funded by toll-revenue bonds. Buses and three-plus carpools continue to use the Katy Freeway HOT lane free of charge at all times and single-occupant vehicles can use the HOT lanes for a charge. Two-plus carpools may use the lane without charge during the morning and evening rush hours. Non HOV users can only use the managed lanes as a toll customer if they have an EZ Tag or TxTag. Currently, pricing on the Katy Managed Lanes follows a set published toll schedule that changes at designated times during peak periods. It is proposed that sometime during 2012, the system will change to a real-time dynamic pricing system that monitors activity on the managed lanes, with tolls increasing for single drivers as traffic increases in the lanes.

In fall 2000, Houston Metro launched *QuickRide* operations on a second HOV facility in Houston: the Northwest Freeway, or US 290, which connects the northwest suburbs of Houston with downtown, feeding into the I-610 loop and running for 13.5 miles. Like the Katy Freeway, the Northwest Freeway had hosted an HOV lane for over a decade prior to QuickRide. Between September 1997 and April 1999, the lane witnessed a 37% increase in the number of peak hour vehicles. This rapid increase, particularly during the morning rush hour, resulted in average speeds in the HOV-lane to slow to less than 30 mph, impacting buses as well as cars using these lanes. Commuter complaints to Metro noted deteriorating operations, delays, reliability problems, and lateness. So, like the Katy Freeway, the Northwest Freeway redefined the lane to HOV-3 from HOV-2. In 2000, the extra capacity from the conversion to HOV-3 was opened to paying two-plus carpools, and it continues to operate on this basis, making the Northwest Freeway Houston's second HOT facility.

2.1.2.4. Miami-Ft. Lauderdale I-95 corridor. The Miami-Ft. Lauderdale region has a 21-mile express lane facility on I-95, between I-395 and I-595. This consists of 2 toll lanes in each direction by a conversion of an existing HOV lane to a HOT (High Occupancy Toll) Express Lane and the addition of a new HOT Express Lane. The Express lanes which opened in 2008 extend from I-395 northward to the Golden Glades Interchange in northern Miami-Dade County. Phase 2 of the project will begin in early 2011 and will extend them to Broward Boulevard in Ft. Lauderdale. The Florida Department of Transportation is also studying the costs and impacts of extending the I-95 Express Lanes north to West Palm Beach. The lanes are congestion-priced throughout the day using traffic responsive tolling algorithms intended to maintain free-flow conditions. These lanes also incentivize the formation of carpools, and transit use by offering toll-free use of the facility to all eligible vehicles. At the same time as the conversion to Express Lanes, the HOV2+ designation was converted to a HOV3+ lane restriction.

2.1.2.5. SR-167 in Seattle, Washington. HOT lanes began operating in May 2008, with a single HOT lane running in each direction of SR 167 for approximately nine miles between Renton and Auburn. By paying an electronic toll, anyone with a *Good To Go!* Transponder can use the carpool lanes. Prices are set so that an average speed of 45 mph or greater is maintained. The tolls range from as low as 50 cents to up to $9.00 during periods of heavy congestion. The toll rate can change based on congestion factors, time of day, traffic volumes, and traffic flow. Customers can anticipate that tolls will be in effect on the HOT Lane between 5 a.m. and 7 p.m. The *Good To Go* system was instituted as a four year pilot project and the use of future use of these lanes will be determined at the completion of the study.

2.1.2.6. I-495 (Capital Beltway). Construction of HOT lanes around the Nation's capital began in 2009. The I-495 Virginia HOT Lanes

Project includes two new lanes in each direction from the Springfield Interchange to just north of the Dulles Toll Road and includes the replacement of more than $260 million in aging infrastructure, including the replacement of more than 50 bridges, overpasses, and major interchanges. Virginia Department of Transportation claims "Tolls for the HOT lanes will change according to traffic conditions to regulate demand for the lanes and assure these lanes are congestion free—even during peak hours. When traffic increases, tolls will go up. When traffic decreases, tolls will go down." Buses, HOV3+ carpool vehicles, and motorcycles will use these lanes without charge.

2.1.2.7. Proposed HOT Lanes in US. A number of other locations are studying initiatives for HOT lanes. These include the construction of HOT lanes in Minneapolis, Minnesota; Georgia; Texas; and Seattle, Washington; and the expansion of HOT to other major highways in Florida, California, and Virginia.

2.1.3. Current thinking regarding congestion pricing for highways

Road pricing cannot be done in isolation. It must be complemented by a comprehensive strategy surrounding supply (roads, public transport, walking/cycling) and management (network maintenance, high quality information systems, fair policing of rules). With proper planning and work to obtain public approval and understanding, road pricing can form a core part of a comprehensive congestion management strategy by

- Placing a value on a scarce resource,
- Reallocating demand patterns,
- Making public transportation more attractive,
- Reducing net costs for freight movement by reducing congestion costs of this transport,
- Reducing emissions from road traffic.

Road pricing also generates revenue that can be used to

- fund additional capacity,
- improve the quality and management of existing capacity,
- fund alternative modes of transportation.

As demonstrated by surveys conducted in the states of Washington, Minnesota, and Florida, a majority of motorists in many congested areas are willing to pay to avoid congestion, with no statistical correlation evident between income levels and willingness to pay. The General Accounting Office concludes:

> "Congestion pricing can potentially reduce congestion by providing incentives for drivers to shift trips to off-peak periods, use less congested routes, or use alternative modes, thereby spreading out demand for available transportation infrastructure. Congestion pricing also has the potential to create other benefits, such as generating revenue to help fund transportation investment. Possible challenges to implementing congestion pricing include current statutory restrictions limiting the use of congestion pricing, and concerns about equity and fairness across income groups. In theory, equity and fairness concerns could be mitigated depending on how the revenues that are generated are used… Some projects have shown substantial usage by low-income groups, and other projects have used revenues generated to subsidize low-cost transportation options. In addition, some recent proposals for refining congestion-pricing techniques have incorporated further strategies for overcoming equity concerns." (GAO, 2003).

2.1.4. Cordon pricing or area pricing

In this section, we will consider both "cordon tolls" and "area tolls." Under area-based pricing, users pay a one-time fee for the privilege to freely use a controlled area or restricted zone of a road network during a specified time period. Under cordon pricing, users pay a fixed amount (flat toll) to enter or exit the area but the charge does not consider the distance traveled or time used within the charged area. A third approach considers a two-part pricing whereby users pay both an access fee and a fee based on the distance traveled inside the restricted area. Tolls can vary by time of day (peak pricing) or be fixed. The tolls can be collected by simply requiring vehicles driven within the area to display a pass, using some technology to capture the license of the vehicle and subsequently charging the user, or by tolling at each entrance to the area.

In 1975, Singapore implemented the first cordon-based variable pricing approach to reduce congestion in the city's central business district. Initially, this was a manual scheme based on paper permits and charged a daily fee for a vehicle to enter the business district during morning rush hour. Since 1997, this system has been electronic and operates most of the day (6:30 a.m.–7:30 p.m.) with higher fees during more congested hours. The toll is charged each time a vehicle enters the business district with the exception that once a specified amount of toll has been reached, the vehicle can enter or exit the city at no additional charge. In addition to the tolling that takes place, there is an upfront ownership tax (custom duties and registration fees which amount to almost 1.5 times the cost of the car) and a vehicle quota system that allows little growth in the car population. The government contracted to a private company to assess fees that assure that traffic speeds are obeyed with flows measured by 2-km road segments. Speeds are based on both safety and environmental considerations. Whenever a metric was not satisfied, penalty points were assessed. The government had the right to revoke the contract if problems were not corrected. The success of this transportation-tolling system resulted in a number of other cities, especially in Europe, adopting similar cordon pricing approaches. For more on the Singapore system, see Keong (2002) and Akiyama et al. (2004).

In 1998, Rome, Italy, implemented a similar cordon-based pricing scheme in order to reduce traffic in the historical areas. Rome now has five concentric zones emanating from the historic area. As one gets closer to the center, there are greater constraints on the number and type of vehicles allowed, severely limiting large trucks and other highly polluting vehicles. In the historic core, measures have been implemented to restrict access by private cars and to improve public transportation. Within the a "Railway Ring", parking prices further restrict automobile use. Along the "Ring Road", an extensive system of park-and-ride lots and public transport improvements encourage commuters and tourists to use public transportation. Rome enforces its rules through a system of transponders and enforcement cameras that use vehicle license-plate-recognition software. The access control system became fully operational in 2001. Permits vary based on the ownership of the vehicle: resident, nonresident, disabled, taxi, delivery, etc. Without a permit, no access is allowed to the center of the city.

Rome has a central transportation management authority that coordinates all bus, rail, and tram services, and is also responsible for traffic management. It provides integrated traffic, congestion, and route information through web, cell phones, kiosks, onboard displays, and in-terminal monitors. The system provides updates on bus and subway service by cell phone, on websites and through electronic signage. Payments are made electronically via smart cards. Holders of annual METREBUS multimodal tickets can park free at the park-and-ride lots (13,000 spaces) and use public transport to access Rome.

Norway encouraged the managers of each major city's transportation system to create pricing mechanisms that fund new roads, improvements to public transportation, and better parking

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near public transportation stations. To obtain funding for these pilot projects, the city was required to provide a complete audit of the use of its roads, mass transit, and traffic throughout the study period. It must perform an audit of all fees collected and detail who is using each component of their transportation system. Each of Norway's three major cities chose alternative approaches to the problem. In each city, the pricing system expires every 10 years and, in order for a system to be continued, the city must get public approval to renew the system.

The first Norwegian urban toll ring was established in Bergen, the second largest city in Norway. Bergen implemented cordon pricing in 1986 as both a new revenue source for road construction and to create a more pedestrian-friendly and environmentally cleaner city. Bergen has seen a 6–7% drop in traffic since implementation. The system is in operation from 6 a.m. to 10 p.m. weekdays. Payments are made when one enters the city with 13% of the revenue being used to cover operating costs. In Bergen, the initial toll pricing expired in 2001 but was renewed for another 10 years. During the renewal process, the way in which fees were distributed changed; now only 45% of the net revenues can be used for road infrastructure investment and the remaining 55% must go to environmental improvements in the city center, including building light rail, and subsidizing mass transit ticket prices. The agreement included building a new 4-lane motorway linking the city with the airport and other industrial parks. In addition to the tolls for entering the city, the city increased substantially the parking tolls.

In Oslo, a toll ring was set up in order to alleviate the choking road traffic conditions on the main road network in and around the city. It was also used to publicly finance infrastructure projects. The original proposal argued for the funding of approximately 50 road construction projects. The enacted compromise legislation resulted in 20% of the revenues being earmarked for public transport infrastructure projects (bus and metro terminals, new metro lines, etc.). For both economic and political reasons, Oslo decided to place the toll ring halfway between the city border and the city center. To assure that no one could enter the city center without paying the requisite toll, four minor roads were closed. The Oslo toll ring has 19 toll stations circling the center of Oslo with drivers paying a fee when passing the toll cordon line. Leaving the city center is free. This cordon-pricing scheme expired in 2007. A new trial was initiated in 2008. Again, the main aim of the scheme was to raise funds for road investments, with 20% of the revenues again earmarked for public transportation. Current revenue is approximately 1 billion NKr with operational costs running at approximately 10% of the total revenue. The tolling system has reduced overall traffic by 3–5%, and increased public transport by 6–9%. The 20% earmarked for infrastructure and public transport projects has created pedestrian walks, reduced noise and pollution, and improved traffic safety. Since the main goal was not to significantly reduce traffic in the city, the trial project is considered by many to be a success.

Trondheim was the third city to build an urban toll ring. The project, from its inception, considered using electronic tolling and included plans for the city's future infrastructure: roads, pedestrian and bicyclist networks, and improved public transit. The system became operational in 1991. When the project was first announced, 70% of the general public was opposed to it. Now, those living in the city and those living in outer environs are about evenly split on its success. Local retailers in the city center were especially concerned that they would lose business. However, with the redevelopment of the city center rather than new development at the edge of the city, residents and retail owners are far happier. For more on the Norway experience, see Ieromonachou et al. (2006).

In Stockholm, Sweden, the national government invested £270 million to create a cordon pricing approach to traffic management. The stated primary objectives were to reduce traffic congestion by 10–15%, improve the environment, and increase accessibility. A cordon was established around the innermost islands of the archipelago with 18 charging points. Charges range from US$1.33 to US$2.66 (SEK10–SEK20) for each crossing of the cordon, depending on the time of day. The maximum charge is US$8.00 (SEK60) per day. Crossings are estimated at 500,000 a day. During the trial period in 2007, congestion was reduced by 20–25%, queue times were reduced by 30–35% in and near the city, and CO_2 emissions fell by 10–14% in the city and 2–3% in the countryside.

In 2004, London, England, implemented a Central London Congestion Charging Scheme that involves an area-pricing program to charge vehicles at the center of London. The process began in 1997 when the new Labour government announced that local authorities would be allowed to implement tolling and keep the revenues for at least 10 years. At that time, London's mayor, Ken Livingstone, believed that implementation of this tolling approach could reduce congestion, make improvements in public transport, improve travel time reliability, and make the distribution of goods more efficient. He therefore believed that cordon pricing would be critical to his approval as mayor.

In 2007, those entering London were charged a flat fee of £8 per day, weekdays from 7 a.m. to 6:30 p.m. This fee is an increase from a previous fee of £5 in July 2005. Enforcement is by cameras that match vehicle registration to drivers. Users can pay daily, weekly, monthly, or annually through the Internet, cell phone, call center, or retail outlets throughout London. Residents who live within the charging zone are eligible for a 90% fee reduction. In 2006/2007 the scheme generated net revenues of £130 million, which were spent mostly on improved bus services. Congestion in the charging zone has been reduced by 30% and there has been a 30% reduction in the number of cars (65,000 fewer car movements). There has been a 20% increase in the movements of buses, coaches, and taxis and an increase of 29,000 bus passengers entering zone during morning peak. Finally, bus reliability and journey times improved with buses experiencing a 60% decrease in delay. However, the management costs for this system have been relatively high compared to revenues mainly because of the cost of the license plate recognition software and operations. For a summary of a number of studies that review the London experience, see Nash (2007), Leape (2006), and Quddus et al. (2007).

Most recently, Mayor Michael Bloomberg of New York City, New York, lobbied for a plan to charge drivers for downtown access during peak traffic times. The plan would have charged most car drivers $8 and truck drivers $21 to drive into the city's downtown at certain times of the day. The plan received approval by the City Council but was rejected by the state legislature in April 2009. Mayor Bloomberg argues that the state decision has resulted in a loss of $354 million in federal transportation aid, in addition to $500 million in projected annual revenue from the traffic fees. Many believe that the plan failed because a subway fare hike went into effect in March without any promise of improvements to that over-used system. In London, for example, the cordon tolling system was implemented at the same time that bus service was improved—82 new buses were added. In addition, subway and bus fares were lowered in London as part of the overall cordon-pricing package. This most recent experience in the US indicates the importance of obtaining public approval for major changes in roadway management and the coordination of increasing fees for drivers coupled with better mass transit services.

2.1.5. *Managing demand on public transport*

In addition to charging individual cars and trucks access to enter major business centers, many public transport agencies are also charging peak and non-peak tolls for using public transportation. Most systems charge a single fee for access although The Bart System (San Francisco) and the DC Metro System charge based on the distance traveled. For a survey of pricing on transit systems throughout the world see 〈http://www.treehugger.com/files/2009/07/subway-fares-around-the-world.php〉.

2.1.6. Mechanisms for setting congestion prices

The operations research literature has provided a variety of algorithms for the setting of congestion prices; see Yang and Huang (2005) for a recent review of this methodology. The simplest and most direct approach does not consider the network as a whole but rather simulates road traffic on a given corridor under study and determines prices that allow the traffic to flow at a given service rate. A good example of this methodology is provided by the Victoria Transport Policy Institute, see (Litman, 2009). In this paper, the authors describe the process of determining the desired level of service taking into account a number of factors, such as the volume-to-capacity ratio, the impact that larger and heavier vehicles have on the overall flow of traffic, and the impact that the configuration of the road and resulting accidents might have on the overall flow. This paper provides a very good summary of the issues that transportation managers are likely to consider when determining the level-of-service. Once the level of service has been determined, prices are calculated based on historical data and perceived user behavior with a given set of prices to determine a price whereby traffic flows at a satisfactory rate. Tolls are updated whenever it is found that the standard is either not being met or when the tolls are found to be too high and traffic flow can be maintained at a lower tolling price. The Victoria Transport Institute (2009) concludes

> Congestion pricing (also called *value pricing*) is intended to reduce traffic volumes to optimal levels on each roadway, which typically means LOS C (sic level-of-service grade C), or about 1500 vehicles-per-hour on grade-separated highways and 800 vehicles-per-hour on urban arterials. The magnitude of fees needed to achieve this depends on many factors, including total travel demand on the corridor and the quality of travel options (such as alternative roads, and grade-separated transit services and HOV lanes), and varies significantly over time, from zero during off-peak periods to more than 20¢ per vehicle-mile on major congested corridors. Fees should reflect the congestion impacts each vehicle imposes on other road users, with higher fees for larger and slower accelerating vehicles. However, fees can also be set using pragmatic objectives such as reducing automobile traffic enough to allow a lane to be re-allocated for transit. Note that there is no reason that total congestion fees should equal the total estimated congestion costs described below.

A paper by May and Milne (2000) also provides a discussion about the process of determining cordon prices for the cities of Cambridge and York and how the computer simulation SATURN that was used to consider four alternative pricing approaches (cordon pricing, distance pricing, time-based pricing, and congestion pricing). Saturn is a steady-state equilibrium assignment model which predicts route choice and traffic flows on a road network based on the costs of travel, taking account of detailed junction delay information—was used to consider the detailed traffic effects of alternative pricing approaches. They conclude:

> "Cordon pricing imposes low charges on movements within the city center and the highest charges for movements between external areas and the city center. Distance and time based pricing share similar impacts, spreading charges more evenly across trip types. Congestion pricing imposes the lowest charges and is the only system to differentiate between inbound and outbound movements… All regimes reduce travel times within the city but increase them to and from external areas. Congestion pricing achieves the smallest reductions, while cordon pricing imposes the largest increases. All regimes produce substantial reductions in delayed time, with congestion pricing being the most effective and cordon pricing the least."

These simulation and static equilibrium model approaches described above differ significantly from the more sophisticated models proposed in both the economic and operations research literature. Economists argue that one should set tolls such that users are charged the cost that they impose on the system. Such approaches are often referred to as "first best" approaches since they are designed to reduce travel delay to the minimum level possible (Hearn and Ramana, 1998). More sophisticated models consider how to develop prices on roads that have highly variable congestion, how to model travelers using multi-model transportation alternatives, and how to price sections of roads when there is a requirement that users will not abide by a system optimal solution if it makes them worse off than using an alternative route. When considering these more-sophisticated cases, the optimization problems become very difficult to solve and few transportation managers apply them. For more on this research, see the seminal papers of Hearn and Yildirim (2001), LeBlanc et al. (1975), and Dial (1999). Many of these modeling efforts use either bi-level optimization or mathematical programming with equilibrium constraints (MPEC). In the bi-level optimization the lower-level model determines the users' route choices based on specified tolls while the upper-level problem determines the optimal road tolls given the users' route choice behavior. For an overview of such equilibrium modeling see Florian and Hearn (1995), Bard (1998), and (Lawphongpanich and Yin, 2007a, b, 2009). For "second price" models whereby not all roads in the network can be tolled (e.g. area-based, cordon based, and pricing of HOT lanes) see (Lawphongpanich and Hearn, 2004; Luo et al., 1996).

As Grush and Roth (2008) state "There is a substantial literature on how to calculate the prices that optimize the use of congested roads… but little on how prices for road use are determined in practice". Operators of the priced segments of Routes SR-91 and I-15 in Southern California charge prices designed to offer uncongested travel corresponding to a Level of Service "C". In Minnesota, Program Manager Ken Buckeye of the Minnesota Department of Transportation reported (unpublished data) that Minnesota aims to achieve on its I-394 MnPASS toll lanes traffic speeds in the range 50–55 mph, which are also consistent with Level of Service C.

It seems as if most road system managers either set a fixed rate for given times and keep the toll constant throughout that period (e.g. Port of NY/NJ) or monitor the roadway and raise and lower tolls based on observed traffic. We could find nothing in the literature or on the web that described the use of the vast operations research and economics models and methods proposed to handle these complicated equilibrium problems. Although most agencies that have imposed congestion prices speak to the social benefit issue, there is little that evaluates the prices set to this objective.

These conclusions may be based on the fact that prices are often set based on many conflicting political and social goals. Regulations may limit the maximum allowable toll, may restrict who can be charged and when, and may require that the revenue from the tolling go toward funding things other than transportation.

2.1.7. Conclusions regarding congestion pricing for managing road and urban congestion

When evaluating the congestion pricing approaches for managing road congestion, we find that there are a number of things that can vary:

1. The mechanism by which one restricts entrance into the system.

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2. The timing of the charges.
3. Where the funds for building the system come from: are they from the state, the federal government, private–public partnerships? Are they collected in an equitable fashion, i.e. do those that contribute most to the system get the greatest benefit from the system? How are cross-subsidies treated?
4. Where the revenues go: revenues can go to improving the road network, improving other means of transportation, supporting inter-modal transportation through, for example, park-and-ride facilities, or to improving the city infrastructure.
5. How the funds are collected: do intelligent electronic systems improve the process? What percentage of the revenues goes toward maintenance operations and what percentage is usable for improvements to the transportation system and/or regional development?
6. The goals of the system and the metrics used to judge success/failure.
7. The processes that were used to gain political and public acceptance.
8. The amount of the charges, the times that the fees are in force, and who collects the funds.
9. The determination of what parts of the transportation system will be tolled, what types of construction will be considered, and what technologies will be used for payment and for monitoring enforcement.

These policy issues are important and one size does not fit all. Thus, regional planners need to assess the existing situation and determine how to obtain the best result. Often, one will need to improve a number of components of the overall transportation system simultaneously in order to obtain acceptance of a new pricing policy. The benefits can be much larger than the reduction in delay times or throughput. They can include business expansion in the region, improvement in quality of life for residents, improvement in air quality, and reduction in road accidents.

Technology is making more complicated price structures possible. Transponders and automatic license matching make the collection of fees far simpler. Electronic systems allow for the minute-by-minute monitoring and verification of speeds at a variety of locations, thereby making price updates possible in real-time. Such updates in price allow the guarantee of reliable speed. For a more detailed discussion of electronic tolling and the available technologies, see Sorensen and Taylor (2006).

Private participation in the building and operating of the road infrastructure has been increasing over time. Austria, Denmark, France, Greece, Italy, Norway, Portugal, and Spain have been managing toll roads through private concessions. Usually, the contractor has been provided a fixed-term right with the bidder who offers to build and manage the road at the lowest toll winning the contract. Many of these contracts have had to be re-negotiated and the manner in which the toll structure is changed may be exactly opposite to general economic principles. Namely, when demand is low the concessionaire asks for price increases; when demand is high, public opinion clamors for price reductions. Thus, the use of private–public partnerships for these activities has issues that may require careful attention. See De Rus and Romero (2004) for more on this topic.

Another aspect of the management of these systems that is still not completely solved is the monitoring of HOT lanes for compliance. Since it is difficult for cameras to see into vehicles and determine the number of passengers, most HOT lane systems require police officers to monitor entrances and check for high-occupancy. Some systems require that HOV vehicles use separate entrances from those used by vehicles paying the congestion fee. Regardless of how implemented, there are substantial expenses associated with the monitoring for compliance of a mixed-use (HOV with HOT) lanes.

Funding of these systems remains expensive, especially when construction of new lanes or entrance and exit ramps is necessary. Congestion pricing in Europe has been used to reduce emissions (Stockholm and Rome) or to make cities more pedestrian friendly. In general, congestion pricing is only one part of a long-term transportation package.

There are a number of new partnerships being created that bring urban, suburban, and rural groups together. In such relationships, one must monitor the performance of the system by looking not only at throughput and speed on the tolled lanes but also at other measures such as accessibility, air quality, livability, and economic growth of the region. When the alternative to driving a car into the city center is mainly public transport, one needs to have a public transportation system in place that is capable of handling the majority of that commuter traffic.

In all cases, obtaining public approval is critical and difficult. Common to most of these applications was the attribute that the public was concerned that the government was simply imposing another tax. When users of the system could see improvements (e.g. tolled roads provided congestion-free transportation, public transportation was improved, and congestion on the non-toll roads also improved) public approval increased substantially. For more on the equity issues of tolling, see Ecola and Light (2009), Glazer and Niskanen (2005), and Langmyhr (1997). For a thorough description of the data needed to complete a thorough cost/benefit analysis of road pricing, see Hau (2005).

3. Congestion pricing applications other than road pricing

3.1. Freight pricing

Interestingly, there are virtually no examples of using similar pricing schemes for freight tolling at ports or on rail lines. The one "poster child" for using variable pricing is a pilot project at Los Angeles ports. The General Accounting Office (2003) reports: "One congestion pricing approach is the Off-Peak program created by PierPASS. PierPASS is a not-for-profit company created by marine terminal operators at the Los Angeles and Long Beach ports to address multi-terminal issues such as congestion, security and air quality. In 2005, PierPASS launched the Off-Peak program in an effort to encourage cargo owners to arrange transport during nights and weekends. The program imposes a $50 per 20-foot equivalent unit 'Traffic Mitigation Fee' on loaded containers that are moved during peak hours. According to a PierPass official, the program has resulted in approximately 36 percent of traffic moving at night, taking thousands of truck trips out of daytime freeway traffic patterns, thus alleviating daytime congestion." For more on pricing of ports see Button (1979).

When examining how other countries treat the pricing of ports, a study by Strandenes and Marlow (2004) conclude that ports worldwide usually base their pricing relative to competition with other nearby ports or on a cost-plus model. None have congestion built into the pricing structure. They conclude "existing pricing structures often suffer from trying to satisfy conflicting objectives—economists, ports, governments, and users will all have different views on what constitutes an efficient port tariff. If governments require ports to pay a dividend then the efficient management of assets becomes the goal; economists want to minimize welfare losses; ports want to maximize throughput, and users now insist on transparency of charges and prices which reflect the cost of the services they have used." They conclude that competing goals create tariff structures that are both complex and inefficient. They suggest three alternative pricing

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approaches: congestion pricing, priority pricing, and off-peak hour first-come-first serve pricing.

Thus, although there are a number of research papers that promote congestion pricing as a mechanism to improve the efficiency of rail, long-haul shipping, and ports, except for the PierPass example, we could find no projects that used such pricing.

3.2. Consumer pricing of energy

Smart meters are used to monitor energy within a facility and charge variable rates based on the time of day that the energy is used. The variation in charges reflects the large differences in the cost of generating electricity during peak and non-peak periods. Congestion pricing of energy would not be possible without sophisticated new technologies that can control the use of energy within households and can supply customers with real-time electricity pricing. Meters within “smart homes” have sensors linked to computers that control the use of lights, heating, and air conditioning, and appliances automatically based on the desires of the residents.

Older meters only measure total consumption of electricity over a relatively long period of time. The newer “smart meter technology” can measure use in real time and can allow power companies to set prices based on the time of day and the season. Power companies have a variety of sources for the generation with some having high-fixed costs but relatively low marginal costs, while other power sources have much higher marginal costs but small fixed costs. Power companies use the high marginal cost generators only during peak periods. The idea is to incentivize consumers to use high load appliances on off hours and to be cognizant of the amount of energy that air conditioners, washing machines and dryers, hot water heaters, and other appliances have on their electricity charges. Thus, with these newer meters, consumers pay significantly more for use of high-load appliances during peak periods but pay significantly less during off-peak hours.

The first use of a smart grid and metering system occurred in Italy. Reports indicate that it has resulted in annual savings of 500 million Euros per year at a project cost of 2.1 billion Euros (NETL, 2008). Similarly, the city of Austin, Texas, is in the process of supplying its residents with smart meters that communicate by a wireless network. In 2010, 500,000 smart meters were operational. These meters have the ability to connect to a home automation network that can control appliances and electrical outlets. Boulder, Colorado, is in the process of implementing a similar system. Similarly, Ontario, Canada, is implementing a system that is expected to serve 1.3 million customers in the province of Ontario. A statistical study of 400 sites in that region with smart meters showed a 6.5% savings compared with a similar size of non-smart meters.

A paper contracted by the US Department of Energy compared the electricity use of those with smart meters and those without over a 5 year period; see Parker et al. (2007) for complete details. They carefully examined 17 sites where smart meters were installed and for which there was a nearly identical site (same neighborhood, same energy usage prior to the study, etc.) where there was no such smart meter installed. For those in the study, they examined usage over a 5 year period: 3 years prior to installation and 2 years after installation. They found that there was an average savings from the energy feedback monitors of 7.4%. Generally, the homes with the largest consumption also experienced the largest savings.

A study performed by Charles River Associates examined the results of a statewide energy pricing pilot program (George and Faruqui, 2005). They found that statewide, the residential peak energy demand on critical days was reduced by 13%, with the impact being twice as large in the hotter climate areas than in the cooler areas of the state with the results consistent across two summers. Demand responses were highest among higher income families and among those with air conditioning. The satisfaction among those that were involved in the energy pricing pilot program was high. They perceived that the rates were “fair”. Most importantly, they indicated a preference to continue with the new rate system after the pilot period. Interestingly, appealing for load reductions during critical days in the absence of price incentives did not result in sustainable demand responses.

In October, 2009, California passed the first statewide Smart Grid bill in the US. Senate Bill 17 required the state’s Public Utilities Commission (PUC) to develop a plan for Smart Grid deployment throughout the state by July 1, 2010 and for utilities with more than 100,000 customers to create their own timelines for deployment by July 1, 2011. The PUC is required to report, on a yearly basis, to the governor and the legislature the progress being made. Even before this legislation passed, San Diego Gas and Electric, Pacific Gas and Electric (PG & E) and Edison International each had smart grid programs. By 2010, PG & E had installed 3.7 million smart meters throughout its coverage area in Northern California. In 2010, California obtained funding from the stimulus package to continue this effort.

The limited studies completed on this topic indicate that technology has the potential to reduce energy consumption through a pricing policy that encourages off-peak use. Studies show, however, that the changes in use are highly variable. Education is critically important. Also, to changes in regulatory policy to incentivize the energy companies to encourage a drop in energy use are required. Currently, many energy companies earn their profit based on increases in energy use and the resulting expansion of power generation plants—a capital investment for which the power company gets a return on investment.

The movement toward a smarter grid and smart meters seems likely. However, there must be funds that allow a better connection across the entire US grid with smarter switching devices. There is currently, within the Economic Stimulus Package of 2009, $3.4 billion in stimulus grants to utilities working on Smart Grid initiatives. Other funding is available to better connect the US electricity grid. Such changes are likely to hasten the sue of congestion pricing within the energy industry.

3.3. Other consumer pricing that incorporates congestion

Examples of congestion pricing within the private sector include revenue management pricing practices within the hotel and airline industry, cellular phone use, and the purchasing of goods and services during shoulder and off-peak times (e.g. end-of-season sales, off-season installation of heating or air-conditioning units, etc.). This paper is concerned only with government uses of congestion prices and so will not survey these revenue management applications. The success of these pricing schemes is their ability to create pricing structures that anticipate high and low demand periods and to predict what set of their customers are willing to shift their demand. For a recent survey of revenue pricing methodology and applications see Talluri and Ryzin (2005).

4. Congestion pricing for air transportation

The US air transportation system suffers from high levels of congestion and delay. In 2008, only 70% of flights arrived at their destination on time.[1] Economists characterize this delay as a

[1] US DOT, Bureau of Transportation Statistics. 〈http://www.transtats.bts.gov/HomeDrillChart.asp〉.

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result of market failure. Airlines fail to internalize the full costs of their airport and airspace usage because the access costs that they pay do not include the marginal delay costs that their actions impose on other users. Airlines currently pay a weight-based landing fee. Landing fees are inefficient because they do not include any congestion costs or other externalities; see Murphy and Worth (2001).

For the most part, access to airports and airspace in the United States is currently allocated on a first-come, first-served basis. There are a few airports (the three New York airports and Reagan National Airport in Washington, DC) that operate on a slot system due to high demand for limited capacity. Slots are defined to be the right to schedule a flight departure or arrival at a given airport within a given period. Slot capacity is based on runway capacity and slots are administratively allocated to airlines based on past usage of the airport.

The practice of administratively allocating slots (at the few US airports with slot programs) through the use of grandfathering encourages the inefficient use of airport resources. Slot holders have incentives to use slots inefficiently solely to preserve them for future use or to discourage competition. A report by DotEcon (2001) concludes that grandfathering slots serves as a barrier to entry. They further conclude that any type of administrative slot allocation procedure is inefficient because it is extremely costly or impossible for the administrator to determine the relative social benefit that users could produce from a slot.

Brueckner and Van Dendera (2008) use evidence from slot control programs at JFK, LGA, and ORD to demonstrate the ineffectiveness of the current system of managing airport access rights. The relaxation of the FAA slot controls at these airports in early 2001 led to a surge in flights, accompanied by massive delays and forced the re-imposition of slot controls at LaGuardia and O'Hare airports. In both cases, the slot allocation was based on the percentage of scheduled flights at that time. Such regulation encourages the hording of slots in anticipation of any further reduction in access. Brueckner and Verhoef (2009) argue that a market-based allocation would result in better efficiency because it would allocate the slots to those that valued them the most. Such allocation would result in optimal use of the slots.

The impact of setting a service standard for access to runways would have a significant impact on delays. Currently, the FAA accepts all flight plans without limit, except for a few slot-controlled airports. At the slot controlled-airports, the capacity is set at a "perfect" weather day. Thus, at virtually all airports in the US, demand often exceeds the available runway capacities. When this occurs, air-traffic controllers order takeoffs and landings based on the order of arrivals and departures as listed in the published schedule. This is known as "ration-by-schedule." At the busiest US airports, flights later in the day suffer the greatest delay because the queue builds as the day progresses. In order to have passengers less annoyed by this deterioration of service, airlines "pad" their schedules so that, even with delays, the airline arrives "on time" (Rapajic, 2009; Donohue, 2009). An alternative would be to limit airline schedules to more closely align with the observed capacity of runways. A recent regulatory evaluation conducted by the FAA of a plan to reduce operations at LaGuardia Airport found very large benefits from setting a service standard, see (FAA, 2006). Even with a properly set service standard, there will be occasions when severe weather creates additional capacity reductions. Given the stochastic nature of such capacity changes, congestion pricing could then be used to realign demand with supply.

Excess demand for airport capacity has been studied much more intensively than airspace congestion. On bad weather days, congestion problems can worsen throughout the day, as delays cascade from one hour to the next, and can spread quickly to other parts of the National Airspace System (NAS). Airspace congestion occurs in the NAS when loading in sectors approaches or exceeds capacity. Loading and capacity can be difficult to forecast because weather affects both. During periods of severe congestion, the impact of even one flight on NAS performance can be large (Hunter et al., 2007).

Ledyard (2007) examined features of efficient markets that apply to various types of aviation resource allocation system. The proposed tools include both quantity-based and price-based allocation systems. In a quantity-based system, regulators would set the quantity of flights at an appropriate level. A market-based tool would then be used to allocate access among market participants. In a price-based system, regulators would set a price for access that would result in the appropriate level of flights. The goal in either type of system would be to allocate aviation resources to the users that value them the most.

Efficient markets enable trades to be made with low transaction costs, have high liquidity, and are transparent. To set up a market, the property right must be defined, qualified participants must be identified, the market design must be determined, and clearance/settlement mechanisms must be established.

With congestion prices (that reflect marginal delay costs), users will consider the full social costs of their airport/airspace use (including the delay that the flight imposes on other flights) rather than just the private costs that they consider under the current system. Congestion costs would vary over time, due to different levels of delay at different times, and because delays early in the day impact more flights than delays later in the day.

With an auction of limited access permits (or slots), those users willing to pay the most (presumably as a result of having the highest value demand) will gain access. Auctions would improve economic efficiency by forcing slot holders to explicitly value slots and consider the opportunity costs of retaining them. A market based allocation system would reduce the inefficiently high level of airport/airspace use to a lower, more efficient level. In addition to directly influencing congestion levels, market based allocation can signal where capacity should be expanded. If users are willing to pay for access to a resource in excess of its marginal operating costs (through auctions or congestion pricing), then capacity should be expanded if the premium above current operating costs due to the expansion is less than the premium being paid today (Neels, 2002).

Economists believe that either auctions or congestion pricing would result in efficiency gains relative to first-come, first-served or administrative allocation systems. However, economists differ as to what type of market based allocation system would best improve efficiency.

Since airlines have high capital costs—aircraft purchases, crew training, marketing of routes—and since schedules must be announced months in advance of flights, the industry needs predictability. We therefore believe that the allocation of runway access is best handled through long-term auctions with secondary trading. The slot distribution resulting from a slot auction and a secondary trading system will more closely resemble the slot value to carriers than the current-allocation system. In 2008, the FAA developed an explicit program to auction 10% of the slots at each of the three New York Airports. Carriers would receive 90% of their incumbent slots in the form of 10-year leases; the remaining 10% would be auctioned using a sealed bid, second price package format. The auction process was fully developed and demonstrated to the industry on December 5, 2008.[2] The

[2] A bidder seminar was held on December 4, 2008. Information about the auction design can be found within the materials supplied at that seminar. See: 〈http://www.faa.gov/about/office_org/headquarters_offices/aep/ny_auctions/events_calendar/〉.

auction has been challenged in Federal Court and was suspended pending either a ruling or a change in policy by the new administration. In May of 2009, the Secretary of Transportation announced that the auction was to be abandoned because of industry opposition. We maintain that an auction is likely to be the best mechanism for allocating long-term use of runway access. We refer the reader to Ball et al. (2005) and DotEcon (2001) for more discussion of this topic.

Daniel and Pahwa (1997) argue that congestion pricing would be more effective than auctions for the airline application. They argue that because both demand and capacity are stochastic, congestion pricing is a better mechanism. We agree that for day-of-flight operations, congestion pricing could better re-allocate demand when weather further limits capacity below optimal runway capacity.

Through a multi-stage mechanism one is capable of handling both the needed predictability of access and the re-allocation for the day-to-day variations in capacity. The long-term allocation would be done via an auction and secondary trading would allow airlines to readjust the allocation as needed. On the day of operations, when weather reduces the capacity, congestion pricing will encourage the airlines to put the scarce airspace to its best uses with prices being set based on the amount of airspace lost.

Some foundations for the establishment of a market-based allocation of aviation resources on the day-of-flight already exist. For example, the FAA currently uses a process called "cooperative decision making" (CDM) to allow airlines to participate in the decision of which flights to cancel. This system operates on the principle that queue position belongs to an airline operating a flight rather than the specific flight itself (Neels, 2002). Access[3] to the airspace system on the day of flight when capacity is in short supply is defined in terms of arrival slots at airports and/or congested airspace. Both definitions translate primarily into ground holds at the departure airport. On the day of flight, if there is insufficient capacity in a region of airspace, some flights destined there are held at their departure points (ground delay program or GDP). Users are allocated a portion of the available airspace based primarily on the number of flight plans they have in the system that are potentially affected by the shortfall in capacity. All other things being equal, carriers with more flight plans get a larger share of the available capacity than carriers with fewer. Users may choose which flights to operate, so long as they can logistically meet the available capacity (arrive in the appropriate time window). In cases where a user cannot operate within an assigned time window, they are encouraged to turn the access right back to the Traffic Flow Management (TFM) provider, who then allocates it to another user and attempts to replace the traded-in right with a later one that works logistically for the carrier. This process is called cooperative decision-making process or CDM. Ball et al. (2009) suggest an enhancement to the CDM system whereby airlines would also be allowed to swap their access with other airlines. Currently, such swapping is not allowed. Barardino et al. (2011) expand on this idea by allowing monetary trading and trading across airports to take place.

Given that the traffic flow management (TFM) provider would define the amount of capacity available, the provider could also impose tolls on flights in order to reduce demand to the available capacity. The TFM provider could use currently available tools that measure the impact that any flight has on the overall congestion. Thus, it is possible to assess congestion tolls that are based on the amount of congestion that a given flight imposes on the system. This makes sense for a system where, unlike road networks, certain flights have a much greater impact on the system than other flights. For each flight, the traffic flow management provider would rank flights based on their congestion impact to the system and rank the flights accordingly. In the event of a demand-capacity imbalance, it would assess a toll (consistent with these congestion costs) on the most congesting flights. These users would be given a limited amount of time to state whether they intended to fly their announced flight plan, choose to re-file an alternative flight plan that avoids the congested area, or accept a delay. After the first round was completed, the TFM provider would assess the demand–capacity relationships, and assess tolls on another block of flights until the demand–capacity relationship came into equilibrium.

The important distinction between this market design and most congestion pricing schemes is that the TFM provider assesses congestion tolls selectively. The tolls take account of the congestion externality caused by each flight (assuming all flights will operate). Thus, these tolls could easily be different from what a user might be willing to pay in an auction. In order to estimate the correct tolls, only a relatively small number of flights would be assessed a toll in each round; this insures that the computed congestion costs imbedded in the fee are close to those that would actually be incurred. In any round of tolling, some users will opt to pay the toll while others would opt not to. The latter would be delayed and encouraged to re-file for a later departure. With some of the most congesting flights out of the congested time frame, the demand–capacity relationship would be closer to balance. The rounds would continue until balance was reached. Tolls would be adjusted up or down during the process in order to reach equilibrium.

This market design fulfills the two main criteria in the following way:

- A user with a highly congesting flight would be assessed a high toll; if that user were willing to pay the toll, then that interaction between the congestion costs and willingness-to-pay would suggest that it would be given priority in the system and the allocation resources among users would be improved. Without the opportunity to express its willingness-to-pay to pay the toll, that user could have either imposed a congestion on all other users (without compensation) or been precluded from flying entirely by an administrative allocation system.
- The utilization of available airspace would be improved because the most congesting flights would tend to be the ones first removed from the system; as a result, fewer flights would need to be affected by a ground delay or other delay program imposed by the TFM provider.

We are unaware of any country that uses either auctions or congestion pricing to manage airspace or runway congestion. In most countries, access to airports is slot-controlled and capacity is set significantly below runway capacity. By limiting access, the country provides the national airline with a competitive advantage. Deregulation of the airline industry resulted in the ability of airlines to schedule flights well above the capacity of the airspace and runways, even on perfect weather days. We propose market-clearing mechanisms that will better align supply with demand. Such mechanisms are likely to

- put scarce resources to their best uses,
- reduce passenger delays,
- reduce cost of operations to airlines,

[3] For this discussion, we are not focusing on other factors that may adversely affect access at an airport, including long term exclusive contracts, strategic scheduling, or other practices that may inhibit free entry and exit. Some of these factors (e.g. long term contracts) may not easily be influenced by either the Traffic Flow Management provider or the federal government.

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- increase predictability and reliability of travel, thereby increasing usage of this mode of transportation by the highest-paying customers, the business traveler,
- increase economic productivity by removing time wasted,
- determine where new capacity is most needed,
- promote up-gauging of aircraft, thereby increasing throughput without large capital expenditures.

5. Conclusions

This paper has surveyed the use of congestion pricing. There have been a number of recent successes in the use of congestion pricing in road transportation to alleviate peak loads of demand. The use of new technologies has played a major role in these successes because it has provided cheaper and less obtrusive mechanisms for charging the imposed fees and for monitoring compliance. In many of these instances, congestion pricing was used for multiple purposes: alleviating congestion, reducing emissions, improving the livability, and economic welfare of a region. It has often been used to improve mass transit, bicycle paths, and pedestrian walkways. There is much discussion of its use at ports and rail transfer points. Time-of-day pricing of electricity is being implemented in a number of locations and its use is likely to increase as the technology matures.

Surprisingly, except for roads and ports, we could find no examples where congestion pricing was imposed on a specific industry by the government entity that controls that valuable, scarce resource. Rather, when the federal government wishes to allocate a scarce resource to industry (e.g. spectrum, power generation and distribution, grazing or oil exploration on public lands), the allocation is either by auction or negotiation. A companion paper discusses the use of auctions by government to allocate scarce public resources.

For the airspace application, there is a need for long-term use rights (because of high capital investments) and sufficient variability in the process that one might need both auction and congestion pricing mechanisms to best handle all aspects of the allocation process. As with other applications, all technological advances (the ability to predict weather conditions, the ability to estimate the impact that individual flights have on that capacity, and the ability to re-route planes around weather conditions) help in the management of capacity. With such tools, one can better assess prices that will reduce delays most efficiently. Flights that cause more delay incur additional costs than those that have less impact on the system. Airlines are incentivized to up-gauge aircraft and thereby improve overall passenger throughput while simultaneously incurring less costs. The airlines will no longer need to pad their schedules and will therefore reduce costs and provide more predictable operations. And, many of their most valued customers—the business travelers—may choose to fly more often because of the improved reliability of the system.

Future research will test the impact of alternative market mechanisms through human-in-the-loop simulations.

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