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16. ABSTRACT

As technology advances and cities look beyond building roads and transit as a means of reducing congestion, more and more large cities will take congestion pricing into consideration. The extant literature on road pricing is not very focused on the particular facts of zone pricing the application of tolls to entire zones of a city. Also, the extant literature does not have a strong theory of how cities could use usage tolls that take into account how far or how long vehicles travel inside the zone to control congestion, which is an option constantly growing in feasibility.

An extensive survey of prior experience with zone pricing shows that usage tolls are not strictly necessary to create a successful system and relieve congestion a great deal. This is true largely because the congestion problem in large cities is so serious that anything helps. Nonetheless, usage tolls stand to improve matters significantly in two major ways: First, when they vary by time-of-day, usage tolls can encourage people to reschedule their trips productively so that the high-value, short trips are taken at the peak of the rush, and many people can get to work near when they want. Second, such tolls can discourage long trips that use up large amounts of road capacity from using the zone for instance, by encouraging people to drive around the downtown instead of across it.

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Zone pricing in theory and practice: Final Report

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1 Introduction

In 2010, the Transportation Authority Board of the San Francisco Board of Supervisors unanimously approved a report called the Mobility, Access and Pricings Study (MAPS) and recommended further study of its recommendations. Carried out by the San Francisco County Transportation Authority (SFCTA), MAPS centers on the idea of charging drivers to travel in downtown San Francisco at certain times. The goals include curbing auto congestion, increasing bus speeds and raising funds for transportation.

To most people familiar with transportation issues today, the MAPS' recommendation is immediately recognizable as an instance of a class of policies variously called "value pricing," "road pricing," "variable tolling" or, most generally, "congestion pricing." California is, in several ways, a leader in the adoption of congestion pricing. In the twenty years since SR-91 Express Lanes opened in Orange County (which vary tolls to keep speeds high), the project's concept has spread around the state and the country; hundreds of miles of such lanes are now in operation or under construction in many of America's largest cities. The San Francisco-Oakland Bay Bridge has raised tolls at peak hours since 2010. And since 2011, San Francisco's SF Park Program has used occupancy data to vary rates over the day for public parking since 2011, with the goal of cutting cruising for parking and ensuring availability.

This history testifies that American governments and engineers can reliably carry out road pricing on a wide scale in a variety of environments, and that drivers can learn to navigate the technologies involved. The American experience seems to bode well for a project such as MAPS. At the same time, it is important to note that MAPS is of a decidedly different character than the projects Americans have built and used thus far. In fact, its adoption would place San Francisco in a select club of fewer than ten cities worldwide.

At first blush, what distinguishes MAPS is the geography of the infrastructure being priced: other American congestion pricing projects have typically charged drivers to use freeway lanes, while MAPS would cover a whole zone of a city. We call this class of pricing *zone pricing*. Tolling downtown travel is obviously attended by special technical challenges: there might be a great many of access points; and since it is impractical to have unpriced lanes alongside the priced lanes of a downtown (as is common for freeway pricing), zone pricing must deal with drivers who do not have special technology installed on their cars. Moreover, city traffic admits a broader variety of modes: private autos, taxis, delivery trucks, public buses, commuter shuttles, light rail trains, bicycles, pedestrians and wheelchair travelers can all be counted on a single block of a modern downtown.

On closer inspection, however, zone pricing can also be distinguished from freeway and parking pricing by something more fundamental than geography: *dimensionality*. A parking charge incorporates one dimension: time. For the same time, one user cannot not use a parking space more intensely than another. A freeway has, for pricing purposes, only a length dimension. Drivers on Express Lane enter at some location and exit at another, and we may be sure of exactly how much distance they travel in between.

A zone such as downtown San Francisco, by contrast, has a more complicated dimensionality that admits wide variance in how intensely different drivers use the infrastructure and in how much traffic they cause while doing so. For example, some drivers who cross into the Tenderloin may enter by an uncongested street and immediately park their cars in a garage. Even at a busy time of day, such a trip contributes very little to the zone's congestion; and the driver cannot reasonably be said use the street network very intensely. Meanwhile, another driver—a task-runner or delivery driver, for example—may spend all of rush hour driving between destinations in the heart of the Financial District. When the District's traffic density is very high, the latter driver could reasonably waste—cumulatively—whole hours of others drivers' time by this single trip. It also goes without saying that the latter driver is getting more use out of the street network. But in spite of such larger differences in usage and traffic externality, zone pricing schemes (including the MAPS proposal) have not thus far been practically able to charge the two trips differently. Drivers are typically charged for crossing a boundary into or out of the zone, without regard for internal travel.

As an analogy, one may imagine current zone pricing as a power company that charges customers for the act of turning on a lamp, regardless of the bulb's wattage or how long it is on. While such a rate structure would preferable to one that ignored usage completely, it would probably provide a worse service with less fair pricing than customers now enjoy.

Our research centers on the theory of zone pricing, with a special focus on the potential for schemes that take into account differences among how different drivers use the network—how much time they spend or how much travel they do inside the zone. The mission is to set out principles and predictions for an era, not long from now, when advances in technology, growing public familarity with pricing and pressure on governments to relieve congestion without expensive infrastructure will make it feasible to align usage and charges more closely. This final report summarizes the work we have done in that direction. Section 2 surveys the history of zone pricing around the world. Section 3 summarizes a paper published by the authors on the advantages of fine-grained pricing to the optimal scheduling of commute trips. Section 4 summarizes other research on mode choice carried out as part of Mr. Lehe's thesis, Lehe (2016).

2 History: Lehe (2016)

Part of the work made possible by the UC CONNECT grant consists of the first-ever thorough survey of zone pricing, which appears in Lehe (2016). To be sure, there have been written many broad overviews of the practice of road pricing generally (e.g., Anas and Lindsey (2011) and Gómez-Ibáñez and Small (1994)) as well as in-depth descriptions of particular projects (e.g., Santos (2008); Börjesson and Kristoffersson (2015); Eliasson (2014)). But this survey is the first to collect together all of the most recent developments into a narrative that pays special attention to the special challenges of zone pricing.

The idea of pricing a whole zone of a city first garnered interest in the United States and the UK during the 50's and 60's. Buchanan (1952) proposes that, rather than grant blanket drivers licenses that enable driving everywhere, authorities issue drivers licenses for different places at different prices. For example, the Manhattan license might cost a great deal, because the demand for driving there is so high. Later, Britain's Road Research Laboratory was comissioned to evaluate pricing entry to cities, and the result, Ministry of Transport (1964), is full of ingenuous ideas for using the limited technology of the time. One of these proposals became reality—though not in the UK.

Singapore Area License Scheme (ALS)

In the early 1970's, amid soaring household income and car ownership, Singapore was in danger of becoming as congested with car traffic as American cities. As part of a multi-pronged response, in 1975, the government established the "Area License Scheme" (ALS). To enter a "Restricted Zone" (the Central Business District) between 7:30 and 9:30 AM on workdays, the driver of a private, non-carpooling automobile needed to show, in the car's windshield, an up-to-date daily or monthly "license," which was simply a paper ticket sold in books at various stores around the island. To enforce the scheme, wardens would stand by the side of the road at entrance points to the Restricted Zone and write down on clipboards the plate numbers of violators. While simple, ALS immediately cut private car flows by over 70%.

Singapore Eletronic Road Pricing (ERP)

After ALS, there were scattered movements toward a richer system. ALS added charges for different classes of vehicle as well as evening and mid-day charges. From 1985-1985, Hong Kong tested a very precise system that used wireless technology, but it was canceled when the UK agreed to hand Hong Kong over to China, prompting worries about spying. In the late 1980's several Norwegian cities surrounded themselves with electronic tollbooths, but these were designed to make money for road projects, not cut congestion.

In 1997, Singapore replaced ALS with a more adaptable system called Electronic Road Pricing (ERP). It has two cordons—one nested inside the other—around the central business district. All vehicles in Singapore have a device called an In-Vehicle Unit (IU) mounted on the dashboard with a slot for a "Smart Card," which drivers load with credit at 7-Eleven and other stores. When a vehicle passes under a metal archway called a "gantry," the gantry signals the IU, which charges the Smart Card. There are different IU's for different vehicles, so a truck pays several times the toll a motorcycle does. Prices change every half-hour according to a publicized schedule, which is updated quarterly to meet speed targets.

London Congestion Charge (LCC)

Singapore's ERP works well but is hard to copy. In an island city-state with low car ownership, it is easy to put IU's in every car, but not in most developed countries. Fortunately, by the early 2000's, Automatic Number Plate Recognition (ANPR) technology made camera-enforced zone pricing schemes practical and spread zone pricing across Western Europe.

In early 2003, London launched the London Congestion Charge (LCC). It structure is simple: a driver pays a flat charge to drive in Inner London between 7:00 AM and 6:00 PM. Charging is not automatic; rather, to avoid a fine, driver must pay online, in stores or by phone before midnight after entering the zone. There are hundreds of cameras scattered throughout the charging zone, so even purely internal trips are subject to charge. The LCC is distinguished by its high price: the charge has been raised in steps from £5 in 2003 to £11.50 ($16.20) today. The LCC's main achievement has been making London more multimodal in two ways: (i) its revenues have purchased more bus service; (ii) it has let car lanes be converted to bus and bike lanes without hurting traffic, despite a soaring local economy.

Sweden's Congestion Taxes

The Stockholm Congestion Tax started as a 6-month trial in 2006, and after passing a referendum became permanent in 2007. The Tax relies on gantry-mounted cameras in a cordon around central Stockholm, which is easy due to the city's island geography. It has time-varying prices, like Singapore, but the schedule is not updated frequently. Due to the time-varying prices and Stockholm's smaller size, the the Tax has sharply cut congestion while charging much less than the LCC.

In 2013, Gothenburg—Sweden's second largest city—implemented the Gothenburg Congestion Tax. Its design is an almost-exact copy of the Stockholm Congestion Tax (even the toll schedule), and it has produced similar results. The Gothenburg Tax is less popular with the public, however, because most of its revenues are hypothecated for a rail project which has turned out more costly than advertised (Börjesson and Kristoffersson, 2015).

Milan Ecopass and Area C

For most zone pricing systems, environmental benefits are auxilary, but in Milan they are primary. To reign in problems with smog, in 2008 Milan launched a trial of a system called "Ecopass." Ecopass charged different prices to different vehicles according to a schedule of emissions classes, and banned the most high-polluting vehicles. Like Stockholm and Gothenburg, the priced zone is surrounded by gantries holding cameras, but the charge does not vary over the day. The trial lasted three years and was followed by a successful referendum. The system reopened in 2012 with a slightly simpler design and was rebranded "Area C." Gibson and Carnovale (2015) showed that Area C has been highly effective at improving air quality.

3 Trip rescheduling: Daganzo and Lehe (2015)

3.1 Overall scope

Typically, in discussions of road pricing, congestion is treated as a problem of too much driving: the toll is supposed to curb in-flow to a road or network to the point where the negative externality of the marginal trip is muted. At the same time, congestion is also plainly a problem of *when* people travel; it is a scheduling problem. That is to say: if we (with omniscient powers) were to write up a list of the times when each driver enters the downtown in the morning (a "schedule") then if the streets are clogged there may be some other schedule that society and even the drivers would prefer. The question that Daganzo and Lehe (2015) answers is: "By pricing trips of different lengths differently at different times, can a zone pricing system bring about a superior schedule?"

One schedule is said to be better than another to the degree that it (i) saves drivers travel time, and (ii) reduces earliness and lateness. By "earliness and lateness," we mean the gaps between when people would *like to* reach destinations and when they do. The costs of earliness and lateness arise from the benefits of coordinating activities with other people. For example, it is economically productive for a worker to be at work on time because a team member might need face-to-face help. It is emotionally productive to arrive home around 6:00 PM—not 2:00 AM or 2:00 PM—because at 6:00 PM friends and family are there and awake. We call earliness/lateness "schedule delay," the analogue of "travel delay."

3.2 Clarifying the problem

Taken at face value, the scheduling problem is extremely complicated, similar to a problem from theoretical industrial engineering. It also resists any abstraction to principles that policymakers could apply: supposing that some optimal ordering and toll system could be derived for a given population and street network, it is highly unlikely that any actual transportation authority would have the data and fine-grained control needed to put it into practice. Therefore, to simplify things, the study makes a key assumption: authorities would like the toll to keep speed roughly constant over the rush at some target level.

The constant-speed assumption is realistic. Most freeway pricing and zone pricing operations are, in fact, managed with an eye to maintaining target speeds. Because unlike economic welfare, reliability, aggregate delay, fuel consumption or another ostensible target, speed can be measured easily and indisputably. There is less discretion or black-box modelling involved in ascertaining whether a system is hitting a speed target than in measuring these other goals. Nor is it hard to make the public and elected leaders appreciate smoothly-flowing traffic.

The constant-speed target also happens to be well served by developments from the frontiers of traffic flow theory: the Macroscopic Fundamental Diagram (MFD) framework, proposed in Daganzo (2007), verified from data and microsimulation in Geroliminis and Daganzo (2008) and refined in Daganzo and Geroliminis (2008). This framework implies a stable relationship between the average density and speed in downtown network meeting certain criteria, which has been verified by real data and microsimulation.

The existence of an MFD makes it straightforward to think about how to control average speed in a zone. There is no need to model how many cars are on which streets from minute-to-minute. Rather, what matters is the gross number of cars in the network at once, which determines the average density. Consequently, to attain the speed target, the toll needs to ensure there are a constant number of vehicles circulating on the streets of the zone at all times of the rush hour. The number of cars circulating at once is called the *accumulation*.

3.3 A rule-of-thumb for rationing roadspace

Since the accumulation is supposed to stay roughly constant, the zone at any time has only so many "slots" for drivers to occupy. The scheduling problem, then, means rationing which drivers get these slots at which times. Also, since the speed is constant, every driver's trip will take the same amount of time no matter when he or she travels during the rush. The question becomes, "How can a toll allocate roadspace to minimize aggregate earliness and lateness?"

Inevitably, many drivers must be late or early—some very much so. The reason is that most drivers would like to reach or leave work at about the same times-of-day, but not everyone can be in the zone at once without violating the speed goal. We can minimize the cumulative earliness and lateness of everyone, however, by following a fairly simple rule-of-thumb: at the most desirable times-of-day to travel (e.g., 5:15 PM 9:00 AM), roadspace should go to the shortest trips. This is the key insight of Daganzo and Lehe (2015).

By "shortest trips," to be clear, nothing is being said about the *total* length of the trip from start to finish. Trip length in this context refers only to the distance traveled inside the zone. For concrete comparison, a car that drove up from Palo Alto and parked immediately inside SOMA would have a "shorter" trip—in the sense we mean—to a MAPS-like system than one which traveled from the Castro to Embarcadero.

The reason to prioritize short trips is that, for a given speed, the rate at which trips finish will be higher if the network is full of cars making short trips than if it is full of ones making long trips. For example, if traffic moves at 10 mph, and the zone is full of 6,000 cars traveling an averge of .5 miles each, trips will be completed at a rate of 2,000 trips/minute; but if the cars travel an average of 1 mile in the zone, the trip-completion rate will only be 1,000 trips/minute. Suppose, then, that the time is 9:00 AM and that this is the most desired time-of-day to get to work. Aggregate earliness and lateness are minimized if the network at this time is reserved for the .5-mi. trips, and the 1-mile trips travel earlier or later.

To appreciate what this rule-of-thumb would mean in a material sense, note first that a reasonably-drawn zone will have offices, garages and other important trip-attractors concentrated near the zone's center. Planners will not draw the zone's boundaries so as to have such a cluster near the boundary, which would leave a clot of gridlock outside the reach of pricing and delay those entering or leaving the zone. If activity is clustered at the center, then the typical commute trip will be of relatively medium length; it will cut a path between the zone's edge or an off-ramp and the center. Who are the long trips? These will be, to an outsized extent, delivery or service trips (as in Holguín-Veras (2011)) and "through" trips—trips passing through the zone en route to somewhere else. Experience shows that a substantial share of traffic diverted by zone pricing has been through traffic. Consequently, our rule-of-thumb will mean commute trips being rescheduled to the most desired times-of-day, and deliveries and through-trips to less desired ones. A downtown office worker could linger a little longer over breakfast at home, while a drop-off that normally takes place at 9:30 AM would happen at 9:45 AM instead.

3.4 Distance-tolling and its revenues

The key insight of Daganzo and Lehe (2015) is the rule-of-thumb just described—the prioritization of short trips at high-demand times-of-day. There are many toll designs which could conceivably prioritize short trips, and which is best pivots on circumstances. To illustrate how one might work, Daganzo and Lehe (2015) specifies a simple model and compares the performance of a distance-aware toll to a distance-unaware one. We call a toll which does not take distance into account a "trip toll," because it applies "per trip" rather than "per mile."

The trip and distance tolls are compared in an agent-based simulation, which turns out to yield several interesting results. First, as expected, distance tolling succeeds at substantially curtailing schedule delay, relative to the trip toll. With the distance toll, at the most desired time-of-day, drivers are reaching their destinations at an extremely rapid pace. With the trip toll, the distribution is even over the rush, and there are squandered opportunities to reschedule trips.

More surprising, the trip toll succeeds at reducing schedule delay while raising substantially less revenue. The reason is there are different tolls for different trip lengths, and every trip takes place at exactly the time when its tolls is shortest. In fact, as the toll gets more precise, it can succeed (for our very simple model) at eliminating congestion without raising any money whatsoever. Of course, this extreme outcome is special to the deliberately-simple world the paper sketches. The no-revenue result could never happen in reality. But the take-home lesson stands: due to its extra efficacy, a distance toll is able to control congestion without having to charge people very much money.

An argument that low revenues are an advantage

Whether low revenues should be called an advantage or disadvantage is a question for the democratic process. At the very least, authorities will quite reasonably want the tolling system to at least cover its own set-up and operations costs. But they may, in addition, be motivated by the prospect of raising revenue for road and transit improvements: New York City, for instance, is about to implement very basic time-varying tolls for traffic into Manhattan as a congestion reduction tool *and* as a way to fund the MTA's capital costs.

Although infrastructure needs substantially more money in the US, it is the opinion of the authors that low revenue is, on net, a *positive* feature of distance tolls. The argument can begin with the observation that the most important consequence of any pricing scheme is congestion reduction, not revenue: even the extraodinarily expensive London Congestion Charge ($17 today) accounts for only about 4-5% of Transport for London's budget. The money it is feasible to raise through zone pricing in the US pales in comparison to, say, local-option tax measures of the sort paying for the buildouts of the LA Metro and BART. Congestion savings, on the other hand, have been of a size that could only otherwise be achieved by enormously expensive capacity expansion.

It follows that the imperative of toll design should simply be to get a congestion-reducing system up and running, regardless of how much money it brings in (unless it loses money). Ceteris paribus, a low-revenue design stands a better chance than a money-making operation. The reason is politics. A chief obstacle to all pricing schemes—especially ones that take "free" roads and make them tolled like MAPS—is driver political resistance. It is an unfortunate fact of policymaking that not everyone wins from a big change even when most people do; and even when tolling yields large *social* benefits, many drivers will be worse off with tolling than without. The social gains of tolling account for both congestion reduction and government revenue, but drivers enjoy only the former but pay the latter. What a low-revenue design guarantees is that more of the benefits stay in the hands of drivers: they get a better congestion reduction and nonetheless pay less out-of-pocket. No confidence in the ability of government to spend tolls memorably and well is required. Ostensibly, this should weaken some resistance to tolling.

4 Mode shifting: Lehe (2016)

4.1 Sumary of the model

The focus of Daganzo and Lehe (2015) is the scheduling of trips of different lengths. For focus and brevity, that study does not treat the possibility travelers might not drive at all; the question is not *whether* but *when* they inevitably drive.

Lehe (2016) takes a different tack: travelers cannot reschedule their trips within the rush hour, but they can choose not to drive in the rush hour. The goal is to explore the idea that a trip toll—one that does not account for distance-traveled—will tend to discourage the shortest car trips (the trips that travel the least internally). As a result, the trip toll is setting up a less-than-optimal incentive structure: the travelers who quit driving because of the toll are the very ones who contribute *least* to the zone's congestion.

To justify the idea that trip tolls discourage short trips, Lehe (2016) sets up a simple economic model in which travelers choose between driving and transit. Two assumptions affect this choice: (i) driving, with the toll and all other expenses included, is more expensive than taking transit; (ii) transit is slower than driving. Together, these assumptions lead to a trade-off between money and time—the higher fixed cost of driving against its time savings. Since the difference in travel time is caused, not by access or egress times, but by a difference in the speed of each mode, the time disadvantage of transit weighs more heavily on longer trips than short ones. Therefore, travelers making longer trips will find the higher costs of driving to be worthwhile, but not those making short trips.

This is an extremely simplified scenario, but the basic logic can be easily extended down many promising avenues. For example, suppose we limit our treatment to "through trips" that drive across the zone between points external, and replace the transit alternative with the alternative of driving around the zone. In this case, a trip toll will make travelers who would otherwise cut a short chord through the zone's periphery think twice, while those who have to drive down the middle of the zone will not be dissuaded from doing so.

4.2 Policies

These models yield a number of helpful conclusions, of which we will look at two. First, if funds are to be invested in an alternative at the same time zone pricing is implemented, then it will be more effective to spend the money on making the alternative faster than making it cheaper. This is epecially true when the alternative is transit: those who switch from driving to transit due to a toll will tend to have longer trips and a higher willingness-to-pay for time savings than is typical for transit riders; otherwise, these switchers would have been transit riders already. This is not true of everyone, but it explains the success stories of zone pricing well. In London, the rollout of the Congestion Charge coincided with bus improvements that curbed wait times and raised speeds. At the launch of Signapore's ALS, the government franchised both upscale commuter shuttles as well as a cheaper and more time-consuming park-and-ride system; the latter failed immediately.

The same rule can be applied to road investments when avoiding the zone is a chief alternative: projects that provide speedy alternatives to traveling through the zone are especially likely to draw travelers at the margin. London improved the inner-ring road that surrounds the charging zones, and Stockholm is spending its Congestion Tax revenue on a huge underground tunnel making it easier to bypass the city center.

5 Conclusion

In summary, the research funded by this grant has taken a deep look at the details of applying congestion pricing to a whol areas of downtown streets—a practice we call "zone pricing." Section 2 surveyed the history of zone pricing thus far and touched on Singapore's ERP 2.0 scheme, which will charge vehicles for the distance they travel. That possibility—pricing cars for the distance they travel instead of just to enter a high-demand area—has been the focus of our theoretical work. Section 3 summarizes Daganzo and Lehe (2015), already published, which considers the utility of distance tolling for the optimal scheduling of trips. It finds substantial benefits from using tolls to prioritize short trips at times of highest demand, so that the greatest number of people can reach their destinations on time. Section 4.1 summarizes an unpublished research from Lehe's considers how travelers with different trip lengths choose between entering the zone and another alternative—driving around it or taking transit—rather than rescheduling as in Daganzo and Lehe (2015). It finds substantial benefits from using distance tolls instead of trip tolls (though both are far superior to the status quo of gridlock), because trip tolls tend to disproportionately discourage short trips, which contribute less to congestion.

It is the authors' hope that the papers and thesis written with the support of UC CONNECT stand as original and—above all—useful contributions to a topic that is only increasing in importance. There can be little doubt that, in the United States and elsewhere, intelligent tolling will be part of a multi-pronged solution to congestion. Limpid thought about the advantages and disadvantages of various designs will be imperative to the systems' success. We thank UC CONNECT for making this research possible.

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