Congestion Pricing and Information: An Overview

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As long as cars have been on the road, both commuters and economists have fretted about welfare losses due to traffic congestion. In this work, we survey the literature on congestion games, focusing on recent work on information provision in routing. Beginning with the seminal work of Vickrey (1969), economists' preferred remedy to congestion has typically been congestion pricing, the practice of levying tolls on commuters during peak commute hours. However, the rise of routing guidance and ridesharing technologies led authors such as Das, Kamenica and Mirka (2017) to model solutions to congestion as information design problems. We highlight the potential gains of an information design approach to congestion, as well as the complex trade-offs encountered by congestion pricing in empirical work. Keywords: congestion pricing, routing, Braess' paradox, Bayesian persuasion

Traffic costs commuters and economies significantly in time; in the United States alone, the economic costs of traffic congestion have been estimated at around $87 billion per year (Fleming (2018)). With urbanization continuing to create dense, congested cities around the world, as noted in Bryan, Glaeser and Tsivanidis (2020), the costs of traffic congestion remain both a nuisance in daily life and a pressing problem for policymakers to address.

Beginning with Vickrey (1969), economists have typically proposed congestion pricing to reduce congestion. Under most congestion pricing models, commuters pay a variable toll for driving during peak travel times, or for traveling on densely congested roads. Variations on this model have been implemented in several cities, including Stockholm (Eliasson and Mattsson (2006)) and Singapore (Olszewski and Xie (2005)), with notable impacts on average travel times.

However, congestion pricing has also been criticized as a potentiallly regressive tax. If poor individuals commute more often or have less schedule flexibility, the burden of congestion tolls will tend to fall more heavily on low-income commuters. Furthermore, the benefits of reduced congestion may largely accure to high-income individuals who have higher monetary valuations for their time. This has often galvanized political opposition to congestion pricing. Theoretical and empirical work analyzing the regressivity of congestion tolls, including Arnott, de Palma and Lindsey (1994), Small (1983) and Eliasson and Mattsson (2006), generally find that congestion tolls are regressive, but the ultimate effects of a policy depend greatly on the

mechanism used for redistributing a congestion tax's revenues.

Along with the classical literature on congestion models, new technologies such as traffic-aware route guidance and ridesharing platforms have motivated further interest in the field. Among this work, Das, Kamenica and Mirka (2017) and Ostrovsky and Schwarz (2018) study how information provisioning and ridesharing technologies could be used to address congestion, and how these technologies might interact with standard congestion pricing models.

Section 1 introduces the classical models of congestion in road networks and congestion pricing. Section 2 surveys more recent literature on the promises and risks of information provision in routing and congestion problems. Section 3 discusses models inspired by carpooling platforms and the possibility of autonomous vehicles. Section 4 and 5 survey the welfare and distributional effects of congestion pricing, both from purely theoretical models and from several city-specific evaluations of congestion pricing. Finally, Section 6 suggests several open questions for future research in the field.

1. Early Congestion Models

A variety of theoretical work models the behavior of drivers facing congestion. The underlying structure of most of these models is similar, with several differences that authors can tweak in their model. Congestion pricing models generally model a set of consumers and a set of routes, in which

1) Commuters choose between one of several source-to-destination routes.

2) Commuters choose a departure time, given a desired arrival time.

3) Commuters face a travel time that is a function of the number of other commuters on their route.

4) Commuters' utilities are given as a function of travel time and arrival time.

Typically, equilibrium concepts in these theoretical models are restricted to those outcomes where each agent is maximizing their utility while holding other commuters' actions fixed. Despite this basic structure, models vary widely in the details of each component.

The classic congestion pricing model is that of Vickrey (1969) with a single route and homogeneous consumers. Vickrey considers a model with commuters who have homogeneous valuations for time spent in traffic, and time spent at their destination before and after a desired arrival time. He considers one model of congestion: a bottleneck mode, in which a queue gradually accumulates along the route, then is reduced as time progresses and the cars leave. He then considers a variable toll, in which the crossing toll gradually increases as the typical hour of congestion approaches. Under this toll regimen, commuters are indifferent between paying the toll and the (previous) equilibrium in which they remained in traffic. Thus the net surplus is the revenues collected by the toll, with no change to commuters' net welfare. Later modeling work such as Eliasson and Mattsson (2006), deal with the critical issue of how to redistribute these toll revenues.

Arnott, de Palma and Lindsey (1994) extend Vickrey's model to heterogeneous consumers, who can vary along several dimensions. Among their extensions, consumers may vary by their desired arrival time, by their valuation of time spent traveling, and by the disutility incurred from late arrival. This hetero-

geneity is motivated by differences in commuters based on their incomes and type of work. In one example which Arnott et al. give, a manufacturing worker who must clock in at 8:00 am on the dot will likely have an inflexibile response to a congestion toll, whereas a manager with greater schedule flexibility may be able to avoid peak travel tolls. Furthermore, if the worker has a lower value of time, they will likely enjoy fewer benefits of the congestion price than a manager who has a high value of time. Arnott, de Palma and Lindsey (1994) analyze this model and its equity implications, which are discussed in a later section. Building on Vickrey (1969), they also model a simple redistribution of tolls in a lump-sum redistribution.

The more recent work of Das, Kamenica and Mirka (2017) and Ostrovsky and Schwarz (2018) both model road networks with multiple routes between sources and destinations. In these models, a key response of commuters to any congestion price is their ability to choose different routes to their desired destination. However, Arnott, de Palma and Lindsey (1990) models and argues that the efficiency gains of commuters shifting their travel *times* is likely to dominate the effect of commuters shifting their travel *routes*. As in the classical models, most of the recent work on information provision in commuting, such as Das, Kamenica and Mirka (2017) and Acemoglu et al. (2016) continue to focus on road networks with one source and one destination.

2. Information provision in congestion games

With the rise of platforms such as Waze and Google Maps which can provide commuters with real-time information on traffic conditions, economic research on information in routing and congestion games has proliferated in the past decade. Much of this work links to the more broadly construed fields of information economics and information design (for an overview, see Bergemann and Morris (2019)). In particular, the work of Das, Kamenica and Mirka (2017) represents a direct application of the Bayesian Persusasion paradigm first introduced in Kamenica and Gentzkow (2011).

An early study of the effect of information on total congestion times is from Arnott, de Palma and Lindsey (1991), who studied an extension of the classical Vickrey model. In their model, commuters select both a time to depart as well as one of two routes to their destination, which have stochastic congestion levels. They find that if drivers receive perfect information about traffic conditions, total congestion is reduced, but if only incomplete information is provided, total congestion may increase. One intuitive explanation they offer for this is "concentration": if commuters receive common information, they may align on the same choice of route, leading to increased driver concentration and congestion on that route. This finding contrasts somewhat with that of Das, Kamenica and Mirka (2017), who demonstrate a scenario in which complete information provision offers no gains in net congestion time, while well-designed incomplete information provision can reduce total congestion. The comparison of these two models emphasizes the need to carefully design information provision systems for routing games when possible.

Das, Kamenica and Mirka (2017) demonstrate that incomplete provision of information to commuters can reduce total congestion time, when compared to the equilibria under no information or complete information. They model a network where commuters choose be-

tween two routes, one route with stochastic travel time that is not a function of the number of commuters, and one route with a travel time that is a fixed function of the number of commuters. They demonstrate that an information designer can observe congestion times and send a signal to commuters as to which route to take, which does not provide full information yet still results in an improved outcome. Intuitively, when the route unaffected by congestion is better, the information designer always recommends that route. When the route unaffected by congestion is worse, the information designer still sometimes recommends that route, reducing the externalities imposed by drivers taking the route affected by congestion. This is in the spirit of Bayesian Persuasion models laid out in Kamenica and Gentzkow (2011); the design is analogous to that work's leading example of a prosecutor sending a signal to a judge under a set of Bayesian constraints. Das, Kamenica and Mirka also measure the gains from partial information provision against the "price of anarchy" benchmarks introduced in Roughgarden and Tardós (2002).

Acemoglu et al. (2016) study the provision of information in routing games in a different sense than Das, Kamenica and Mirka (2017). In their context, commuters have distinct information sets representing which routes in the network they believe are accessible. Commuters gaining more information is equivalent to having an expanded information set about which routes are available to travel on. Similarly to previous models, the travel times along route segments are determined as functions of the commuters utilizing those segments. Acemoglu et al. (2016) then ask whether commuters being given more information can result in increased total travel times in equilib-

rium. This is an extension of the classic Braess' Paradox (in this case, adding a new route is akin to adding that route to all commuters' information sets), and Acemoglu et al. (2016) dub this an Informational Braess' Paradox.

To analyze equilibrium conditions, Acemoglu et al. (2016) first define a novel equilibrium concept, which they term Information Constrained Wardrop Equilibrium. In this equilibrium concept, commuters take the route in their information set with minimal congestion level, taking the level of congestion on each route as a given. The authors then fully characterize which routing networks are susceptible to the Informational Braess' Paradox. These are exactly those networks which are a series of linearly independent networks, where linearly independent networks are those in which each route has some edge which is not in any other route. They also prove results on the computational efficiency of determining whether a network is a series of linearly indpendent networks, and efficiency bounds on their equilibrium concept.

Acemoglu et al. (2016) also suggest several future directions for research, some of which are linked to those of other work on the provision of information in routing games. In a technical dimension, they note that their work only studies whether commuters with greater information provided to them are themselves harmed by the greater information; it is worth asking to what extent drivers without the given information also suffer greater congestion costs. Both Das, Kamenica and Mirka (2017) and Acemoglu et al. (2016) focus on networks with a single source and single destination, and suggest that further work on multiple sources and multiple destinations is necessary. Finally, they suggest a more empirical lens to determine whether infor-

mational Braess' paradoxes can be detected in the real world, and how likely such susceptible networks are to occur.

3.   Carpooling Models

Recent work has also been stimulated by questions of market design in a near future of autonomous vehicles. Ostrovsky and Schwarz (2018) study the interaction of congestion pricing with carpooling, a practice which they argue will become more widespread with the emergence of autonomous vehicles.

Ostrovsky and Schwarz (2018) first argue that carpooling and tolling are complementary "technologies," which ought to be modelled in conjunction. As a guiding example, they consider the classic Vickrey model of congestion. Under this model, without tolls, agents have no individual incentive to carpool. With tolls and without carpooling, agents are indifferent between paying tolls and waiting in traffic, hence realize no surplus unless the toll revenues are redistributed to them. However, with tolls and carpooling, agents have an incentive to carpool, reducing total congestion on the road.

Ostrovsky and Schwartz next outline conditions that are sufficient for determining when an allocation of riders to routes maximizes social surplus. In their model, an outcome is an allocation of riders to (possibly shared) trips, each of which has a toll cost and a physical cost. Each rider has a valuation for each possible trip. The authors then introduce three conditions on these routing outcomes. They define *budget-balanced* outcomes in the sense most common in the literature. *Stable* outcomes borrow terminology from the literature on coalition formation and stable matchings: if no group of riders can organize an alternative trip that they would prefer, the outcome is stable. Finally, *market-clearing*

outcomes are those in which tolls are only imposed when needed: if a road segment is not at capacity, its toll is zero. This market-clearing condition provides a guide for how to set tolls to maximize social welfare.

One main result of Ostrovsky and Schwarz (2018) paper is that any feasible outcome which is budget-balanced, stable, and market-clearing must be a welfare-maximizing outcome among all feasible outcomes. With more work, they generalize these results to approximate outcomes, which they denote as "quasi-feasible" outcomes, and address some of the technical issues caused by the discrete nature of the problem. Finally, they use their model to compare metrics of "car utilization": they find that increasing the amount of time a car is on the road has relatively small savings compared to increasing the number of passengers in each car ride.

There are several policy implications of the work outlined above. First, when city planners model transit updates and tolls, it is important to model these changes with carpooling considered. Second, their result on surplus-maximizing outcomes suggests that additive per-segment tolls, which do not vary by number of vehicle occupants, are sufficient to achieve optimal outcomes. Finally, their last result serves as further evidence for the power of reducing the friction in carpooling to reduce total cost for passengers.

4.   Welfare Effects of Congestion Pricing

We now turn to the estimated welfare and distribution effects of both theoretical models and empirical work. Along with the wealth of theoretical models of congestion, there is now a wealth of empirical work using measurements of commuter behavior in the real

world. Several of these arise from cities which have implemented congestion pricing systems, such as Stockholm, Singapore, and London. Others, such as Kreindler (2018), measure small-scale interventions in cities that do not have congestion pricing.

Estimating the welfare effects of proposed congestion prices typically requires estimates both of how the prices will change commuter behavior, and of commuters' valuations for travel time and arrival time parameters. Kreindler (2018) collects a panel data set on the travel patterns of commuters in Bangalore, India who were randomly enrolled in one of several congestion pricing treatment groups. Kreindler uses this data principally to estimate commuters' valuations for time and valuations of early arrival time. In a novel step, Kreindler then uses these estimates to estimate the optimal congestion pricing policy, and the resulting change in commuter welfare. He finds that while the optimal congestion pricing policy significantly reduces travel times, its welfare gains are almost entirely offset by the disutility of commuters having to depart at times which they do not prefer.

Kreindler (2018) studies two congestion pricing models in particular: a "departure time" toll, which penalizes drivers who depart at peak hours, and an "area congestion" toll, which penalizes drivers who drive through a particular area (the congested city center). He then models commuters in the spirit of Arnott, de Palma and Lindsey (1994), in which commuters select a route and a departure time, and their choices are guided by their valuations for time and by their scheduel flexibility. With this collected panel data, Kreindler uses a revealed-preference approach to estimate these structural parameters, then simulates the optimal congestion pricing

policy as an equilibrium in which the marginal social cost for a consumer departing at time h is exactly the toll they face.

Kreindler notes that besides being a novel revealed-preference approach to estimate commuters' actual preferences, his is one of relatively few studies on congestion pricing in the developing world. Both Kreindler (2018) and Bryan, Glaeser and Tsivanidis (2020) stress the need for further work on the specifics of congestion pricing in the developing world. At least in this setting, Kreindler's results suggest that congestion pricing may have negligible or harmful welfare impacts, thanks to the undesirable changes it induces in commuters' schedules.

5. *Distributional Effects of Congestion Pricing*

The question of congestion pricing's differential impact on different income groups is critical to analyze. In particular, if poorer individuals tend to commute more and have less schedule flexibility, they may pay the brunt of any congestion toll. Furthermore, as alluded to in Arnott, de Palma and Lindsey (1994), if wealthy individuals have a higher valuation of their time, they will disproportionately benefit from the reduction in congestion. This potential regressivity of a congestion toll is often the issue around which political opposition to congestion pricing coalesces.

Indeed, in congestion pricing models, Arnott, de Palma and Lindsey (1994) found that congestion taxes were likely to be regressive, and surveyed a range of literature finding the same. In their own model, Arnott, de Palma and Lindsey (1994) find that commuters with a higher valuation of their time (concretely, a higher valuation for early arrival and a higher cost of time spent traveling) are

likely to be better off under a socially-optimal tolling regime than those with lower valuations of their time. If these valuations of time are closely related to a commuter's salary, we then expect the toll to be regressive.

In a separate model, Small (1983) also finds that a congestion tax without a mechanism for returning revenues is likely to disproportionately burden low-income groups, primarily due to their lower monetary valuation of time. Notably, this result still holds even though Small (1983) model a public transit alternative in their model, which might be expected to reduce the burden on those commuters facing a congestion toll. However, Small (1983) further models congestion tolls in tandem with one of three plans for redistributing toll revenues to individuals. They find that all individuals are better off if these tolls are redistributed in any of the three schemes. Even under a uniform lump sum redistribution of revenues, they find that benefits of combined time savings and taxes are progressive with regards to income.

Eliasson and Mattsson (2006) focus on the distributional effects arising from congestion pricing. In congestion pricing debates, those resistant to congestion pricing frequently argue that congestion taxes will disproportionately harm the poor, since poor individuals are likely to have longer commutes. The authors model the congestion pricing scheme proposed in Stockholm, Sweden, which was eventually implemented. They find that the most important factor determining whether a congestion tax is regressive or progressive is the use of revenues generated by the toll. In this case, they find that if the Stockholm congestion tax revenues are used to improve public transit, the proposed scheme is actually progressive. They also highlight the importance of modeling public transportation when determining the distributional effects of congestion pricing.

Eliasson and Mattsson first outline the conflicting reasons why a congestion tax might be regressive or progressive. Congestion pricing may be regressive because the wealthy have higher value of time, hence will disproportionately benefit from reduced congestion. Furthemore, the poor may pay more in congestion charges if they drive more often. On the other hand, in cities where autos are faster than public transit, the rich will disproportionately use cars and be affected by the tax. This may be true of "European" city layouts, for example.

The empirical modeling by Eliasson and Mattsson is particularly keen. They deploy several sample enumeration models to predict a commuter's origin and destination zone as a function of each route's travel costs, travel times, and the commuter's income. They use a specialized model of the changes in traffic times for the Stockholm congestion prices to determine these travel costs and travel times, then apply their sample enumeration models to determine predicted consumer charges and travel times before and after the change. These charges can be nicely separated into three categories: charges paid, change in charges due to route shifting, and time savings.

As to the effects of the proposal, wealthy Stockholm residents use their cars far more, hence pay more in tolls and also experience greater time savings. The magnitude of this difference is quite striking, with the authors concluding that "the richest third will pay four times more charges than the poorest third. Taking also time savings and changes in travel pattern into account, the richest third will lose around 2.5 times more than the poorest third from the direct effects of the charges" (618). They stress that the most critical issue in

determining if the tax is regressive, however, is how the revenue collected from the congestion tolls are used. It is worth noting that their work is primarily based on a European model where public transit is widely available, and these results likely do not easily translate to other cities.

6. Potential Research Questions

1) Das, Kamenica and Mirka (2017) study the optimal provision of information to drivers in order to minimize net congestion in various road networks. Das, Kamenica and Mirka find that providing incomplete information to drivers can in fact reduce the societal costs of congestion. However, they note that if multiple firms can provide information to commuters, and commuters are free to switch between information providers, firms may have an incentive to provide (socially suboptimal) complete information. This is important in the real world, given that multiple platforms (e.g. Waze, Google, Apple) compete to provide drivers with congestion information, as Ostrovsky and Schwarz (2018) allude to. **Can we model the behavior of such competitive firms who are providing information in congestion games? Does the presence of multiple firms always lead to full disclosure?**

2) Opponents of congestion pricing often argue that such tolls are regressive, as poorer individuals often have longer commutes and will face tolls more often. Indeed, this has been a key issue in debates around congestion pricing in cities such as Singapore, London, and San Francisco. However, Eliasson and Matts-

son (2006) model a proposed congestion pricing plan in Stockholm, and find that the plan is actually progressive, as wealthy individuals tend to use their cars more often, and poorer individuals tend to use public transit. They attribute this finding to the robust public transportation system in Stockholm, and its traditionally "European" city layout which favors public transit over automobiles. They and other authors caution against drawing the same conclusions in "American" city layouts, where individuals tend to favor cars more often. **Can we more formally characterize what kinds of city layouts and public transit infrastructures result in congestion pricing being regressive? What implications does this have for city planners designing transit networks?**

3) Das, Kamenica and Mirka (2017) appear to be among the only authors to have applied ideas from Bayesian Persuasion to routing games. Their work studies a very specific case with one source, one destination, and a deterministic congestion function. This opens several doors for generalizing the model to incorporate more source and destination nodes, or stochastic congestion functions. One could even imagine modeling or simulating information provision on a road network from an existing city. **When is incomplete provision of congestion information still societally optimal under more complex transit models (multiple routes, nodes, stochastic congestion)? How does the improvement in congestion time**

change under these models?

4) Among the most general work studying when increased information provision harms commuters is that of Acemoglu et al. (2016); they introduce the concept of an Informational Braess' Paradox (IBP) to describe the cases when making some subset of users aware of a route's existence worsens their equilibrium outcomes. However, Acemoglu et al.'s definition of IBP only asks whether the commuters who are provided with more information suffer worse outcomes, not whether other commuters suffer as well. These issues arise empirically as well: routing technologies such as Waze have been criticized for diverting traffic into neighborhoods where residents resent the added congestion. **Can we quantify the externalities imposed by providing information to some subset of commuters? That is, under what conditions does providing information to some commuters worsen equilibrium outcomes for other commuters?** This could take the form of defining a condition similar to that of IBP, then analyzing on what graphs that condition occurs.

5) Kreindler (2018) notes that the model of commuter response to congestion prices, based on their valuation of time and their schedule flexibililty, takes only short-run factors into account. In the long-term, one might expect both commuters and businesses to adjust their behavior in the face of congestion pricing. For commuters, this could include increased work-from-home, shifting working hours, or moving to different locations. For businesses, one could imagine shifts in location, or offering employees different working hours. These shifts could negate any redistributive effects of a congestion toll, and particularly harm the poor: as an analogous example in the field of school choice, Avery and Pathak (2021) demonstrated that thanks to neighborhood relocation, improved school quality under a school choice scheme need not benefit low-income individuals. In this vein, **How do long-term relocation effects affect welfare estimates of congestion pricing policies? Will low-income individuals be most likely to relocate? How does this affect the distributional effects of any congestion pricing scheme?** I suspect that these effects may be relatively small, which could complicate the analysis.

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