Downtown tolls and the distribution of trip lengths

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A B S T R A C T

Currently, all downtown tolls are “access tolls,” meaning they charge for gross access to a zone, but tolls levied on distance-traveled are on the horizon. This paper shows how such tolls affect the distribution of trip lengths. A static model is presented in which travelers with potentially different trip lengths decide whether to drive into a downtown zone governed by a Macroscopic Fundamental Diagram (MFD), with each traveler’s choice probability declining as tolls and travel time rise. An application of Little’s Law allows the model’s equilibria to be derived in terms of a familiar supply/demand framework. Analysis proves and numerical simulation demonstrates that, if trip lengths and the value of a trip both vary across travelers, then access tolls inefficiently shift the distribution of car trip lengths toward longer trips, whereas a distance toll can achieve the welfare-maximizing set of car trips.

1. Introduction

Economists usually recommend road tolls on the principle of marginal cost pricing—the idea that drivers should pay for their delay externalities. On a downtown network, what a rigorous application of this principle would mean is a web of differentiated tolls on every link (Beckmann et al., 1956; Yang and Huang, 1998). Obviously, such precision is impossible in practice. Instead, Singapore (Santos et al., 2004), London (Santos, 2008; Leape, 2006), Stockholm (Eliasson, 2014), Milan (Gibson and Carnovale, 2015) and Gothenburg (Börjesson and Kristoffersson, 2015) have all established downtown tolling systems that charge drivers, not on a link-by-link basis, but for the right to access a downtown zone. Hereafter, such systems will be classified as “access tolls,” because gross “access” to the downtown is what the driver buys from the toll authority. Meanwhile, Singapore has plans in place to switch to a satellite-based system that would charge drivers what will be called a “distance toll,” a charge per km traveled (Tan, 2016). Recently, Sadiq Khan, the Mayor of London, proposed replacing the current London Congestion Charge with some form of a distance toll (Topham, 2017).

This paper was inspired by an observation about how these systems are discussed: often the systems’ initial design and later evaluation emphasizes changes in arrival flows—the gross number of vehicles passing the tolled zone or crossing a cordon around it. As an example, the Stockholm Congestion Tax was designed with the goal of reducing traffic across the cordon by 10–15 percent (Eliasson, 2008, p.396). As another, the designers of Singapore’s Area License Scheme set the toll to reduce morning inbound traffic by 25–30 percent (Watson and Holland, 1978, p. 12).

The problem with this emphasis is that essential characteristics of traffic—its circulation, density and speed—depend, not only on the arrival flow’s magnitude, but also its distribution by trip length. Consider a zone where half of all arriving vehicles park within a few blocks after crossing the boundary, while the other half are ridesharing vehicles that circulate endlessly. That zone could exhibit mild arrival flow alongside severe congestion, while a zone with higher arrival flow might have mild congestion if fewer ridesharing vehicles enter.

Of course, if enacting or raising a toll preserves the arrival flow’s distribution—that is, if it changes the number of trips of all lengths by the same proportion—then change in arrival flow might be a fine proxy of how much the toll change has eased the burden on the street system. But what if toll changes do change the trip length distribution? A little thought shows tolls might reasonably do so, since the rise in speed consequent to a toll change saves longer trips more time than short trips. Of course, with a distance toll, the inequality of travel time savings across trip lengths is attenuated by a money penalty on longer trips, but not with an access toll. To investigate such issues, this paper proposes an original static traffic model designed to show how downtown tolls might alter the trip length distribution and to uncover the consequences of that redistribution for social welfare and measurable traffic variables.

In designing such a model, a principal question is how best to represent traffic physics. One option is to have the downtown network be a graph of origins and destinations connected by links, which might have different capacities and wind up with different congestion levels. This is the approach taken by Meng et al. (2012), Liu et al. (2013), Verhoef (2002), Lawphongpanich and Yin (2012) and other studies in the “second-best” literature on feasible downtown tolls; this literature is devoted...
in large part to solution heuristics and algorithms, owing to the difficulty of finding optimal tolls and equilibrium route flows simultaneously. Similarly, May and Milne (2000) experiments with different toll designs on a simulation of Cambridge. But while potentially useful for engineering real systems, the particularity of network modelling can bury insights that generalize across networks and populations.1 In fact, for a network model it is not even exactly meaningful to speak of how something affects “long trips” or “short trips,” per se; if there is congestion on one side of the network but not the other, then two trips with the same length might have very different durations. Therefore, to avoid network modelling, we assume that traffic is spread sufficiently evenly across the network that a trip’s duration depends only on its distance and on the network’s space-averaged traffic conditions—not on the trip’s origin, destination or route. Under this assumption, the network exhibits a stable relationship among space-averaged flow, density and speed called the Macroscopic Fundamental Diagram (MFD).2 Traffic readings have testified to the existence of MFD’s in Yokohama (Geroliminis and Daganzo, 2008) and Toulouse (Buisson and Ladier, 2009) among other places; and the MFD can even be derived analytically from network parameters in some cases (Daganzo and Geroliminis, 2008; Daganzo and Lehe, 2016).

The MFD approach is a popular one for studies of downtown tolling, and models in this vein—e.g., Small and Chu (2003), Arnott (2013), Geroliminis and Levinson (2009)—are sometimes called “bathtub” or “isotropic” models. What most distinguishes the model here from other isotropic models is (i) the static time character, (ii) variable trip lengths, and (iii) elastic demand arising from a random utility model. The static time character was chosen because dynamic models involve schedule preferences not essential to the topic (the question is whether certain trips are driven, not when) and require certain strong assumptions for tractability.3 One similar study is Arnott and Inci (2010), which also features a static, isotropic model with elastic demand; if all trips were of the same length, then our model would be a special case of Arnott and Inci’s in which parking is supposed to facilitate preclude cruising. Another similar contribution is the elastic demand (Section 3) extension in Fosgerau (2015). In addition to the dynamic character of that model, a major difference here is that our travelers vary not only in their trip lengths but also in the benefit each derives from a car trip. This heterogeneous benefit makes the choice of a traveler with any given trip length probabilistic, so that the aggregate arrival flow of such trips rises smoothly with the trip’s expected utility. As we shall see, this smoothly-changing demand draws out certain inefficiencies of an access toll that are suppressed when either all l-length trips are driven or none are.

The paper is organized as follows: Section 2 sets up the physics and demand mechanics of the model. Section 3 derives the tunelled user equilibrium and shows how to frame the model in terms of both density congestion as well as flow congestion. Section 4 derives the model’s social optimum. Sections 5 and 6 show how to insert distance and access tolls, respectively, into the model and derive useful insights—the most important being that the distance toll can achieve the social optimum but the access toll generally cannot. Section 7 shows how to calculate certain aggregates, for use in Section 8’s numerical simulations. Section 9 concludes with ideas for further research and policy implications.

2. Model setup

This section describes the details of the paper’s main model as composed of two sides: a “physics” side, describing how congestion occurs; and a “demand” side, describing how travelers choose whether to drive. The two sides are then linked by an application of Little’s Law.

2.1. Physics

The setting is a downtown zone governed by a Macroscopic Fundamental Diagram.4 A non-increasing function v(k) (km/min) gives the space-averaged traffic speed v (km/min) for a space-averaged density k (veh/lane-km), but it will be convenient to use the inverse p(k) := 1/v(k) (min/km), which engineers call pace. Minutes are the time-unit, rather than hours, to avoid having pace and circulation be small fractions in simulations. As Fig. 1a shows, p(k) maintains a free-flow pace, p_f, for k < k_0, then rises monotonically.

Let q (veh/min/lane) give the space-averaged “circulation.” By the traffic identity q = kv, there is a function

\[ q(k) := \frac{k}{p(k)} \]  

with the humped shape in Fig. 1b; it reaches a maximum q_0 at k = k_0 (> k_f). For densities k < k_0, blue highlighting denotes what is sometimes called “light congestion,” where q rises as k and p rise. In light congestion, the addition of cars to the road may diminish speed, but not by so much as to lower the circulation. For k > k_0, traffic is “hypercongested,” meaning q falls as p and k rise. In hypercongestion, the addition of cars lowers pace enough that circulation falls.

2.2. Demand

There is a continuum of “travelers” who might potentially drive every minute. A traveler i is characterized by a tuple (ε_i, l_i), where i (km) is its trip length and ε_i (min) is its “gross benefit” from a car trip, measured in minutes of travel time. The utility of a car trip to traveler i, when there are no tolls and the pace of traffic is p, is

\[ U_i = \varepsilon_i - pl_i. \]  

A traveler who chooses not to drive earns utility 0. We will call the choice not to drive the “outside option,” which could ostensibly represent traveling by another mode, choosing a route that does not pass through the downtown, or cancelling the trip. Note that this specification of utility is restrictive in at least two ways: (i) utility is perfectly linear in travel time, and (ii) the value of travel time does not vary across the population.

The population is distributed with joint density f(ε, l). The densities of l and ε are potentially independent, but, arguably, the two properties are likely to be positively correlated: travelers with long trips might be engaged in ridesharing, deliveries or trips to the airport, or they might not have good transit alternatives. The total mass of travelers is λ (veh/min/lane-km), so that

\[ \lambda = \int_{\lambda_f}^{\lambda_0} \int_{\varepsilon_f}^{\varepsilon_0} f(\varepsilon, l) d\varepsilon dl \]  

gives the mass of travelers with gross benefits in [ε_f, ε_0] and trip lengths in [l_f, l_0]. This integral, like all integrals hereafter, is written with the variable of integration in the limits, for clarity.

Before passing to the derivations, we will clarify two points about interpretation. First, the trip length is limited to intrazonal travel only; any travel accomplished en route to the zone or after exiting the zone is outside the scope of the model. Second, due to the static time character, the “population” of travelers cannot be thought of as a single, fixed crowd of people; rather, travelers stand in for a flow of constantly-generated trip opportunities, so the “population” is constantly refreshed with a

1 Similarly, Mun et al. (2003) notes, “Although network models are useful for practical applications, they are not suitable for investigating the general properties of the [pricing] problem, since the results depend on the network structures specified for calculations”.

2 The relationship is also called the Network Fundamental Diagram (e.g., by Mahmassani et al. (2013)) or, splitting the difference, the Network Macroscopic Fundamental Diagram (e.g., by Laval et al. (2017)).

3 See discussions of tractability in Fosgerau (2015), Daganzo and Lehe (2015), Arnott et al. (2016) and Mariote et al. (2017).

4 For further background on the aggregate definitions involved in MFD modelling, see Daganzo (2007).
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