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Dynamic equilibrium at a congestible facility under market power[☆]

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ABSTRACT

This paper studies equilibrium and optimum at a congested facility when firms have market power; e.g., when a few airlines jointly use a congested airport. Unlike most of the previous literature, we characterize the equilibrium in terms of timing of arrivals in a continuous-time congestion model when firms simultaneously schedule services. Using the Henderson-Chu dynamic model of flow congestion in a multiple-firm setting, we find that a stable and unique Nash equilibrium in pure strategies always exists. Importantly, it also exists in cases where it fails to exist under bottleneck congestion (notably when the value of schedule late exceeds the value of travel delays). We find that symmetric firms schedule arrivals inefficiently, and strongly concentrated around the desired arrival time so that the peak is shorter and delays are higher than socially optimal. We show that when firms are asymmetric in terms of output, all firms schedule vehicles in the peak center, around the desired arrival time, with arrival windows increasing with firm size such that a smaller firm's window is always fully contained in a larger firm's window and only the largest firm operates in the early and late shoulders. Furthermore, for any pair of asymmetric firms, the larger firm has a higher instantaneous arrival rate at any moment where both firms schedule arrivals. Our results also show that even though self-internalization can be substantial, there is scope for decentralizing the first-best outcome through time-varying tolls.

1. Introduction

Congestion at airports has recently grown into an important theme in the economics literature. Early contributions by Daniel (1995), Brueckner (2002) and Pels and Verhoef (2004) have brought to the fore that models of road traffic congestion are not directly applicable to the economic analysis of airport congestion. In contrast to atomistic road users, airlines with market power face an incentive to internalize self-imposed congestion. As a result, a traditional Pigouvian toll equal to the marginal external cost would lead to overcharging of congestion, and would have to be corrected by a certain term – one

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minus the airline's market share in a basic Nash–Cournot setting – to secure a socially optimal outcome. Moreover, when airlines with market power have an incentive to also apply demand-related mark-ups in their pricing policies, a further downward adjustment compared to the Pigouvian rule is in order for efficiency reasons.

There is mixed evidence on the degree to which internalization of self-imposed congestion indeed occurs in reality. Mayer and Sinai (2003), for example, provide evidence supporting such "self-internalization", while Daniel and Harback (2008) argue that traffic patterns at airports mostly follow patterns consistent with atomistic behaviour. Several theoretical contributions shed further light on this seemingly contradictory evidence. Notably, Brueckner and Van Dender (2008) show that a Stackelberg leader competing with a competitive fringe of atomistic players would not internalize self-imposed congestion if the products are perfect substitutes. This is because the leader would realize that unused capacity will be filled-up with aircraft from the fringe, leaving congestion unaltered but reducing the leader's profit. Silva and Verhoef (2013) consider Bertrand (rather than Cournot) behaviour of non-atomistic airlines offering imperfect substitutes, and find that also in this case self-internalization is limited, and more so when the products of the competing airlines become closer substitutes. Quite intuitively, a Bertrand player realizes that even when the rival player keeps his fare fixed, the rival's quantity responds to changes in the player's own fare. In particular, increasing its own fare causes an increase in the rival's quantity and therefore increased congestion costs. This makes self-internalization appear less attractive than what it seems under a Cournot assumption of a fixed quantity supplied by the competitor.

Apart from the nature of the game, also some other aspects of the problem have received attention. For example, Basso and Zhang (2007) consider the role of airport capacity choice, Czerny and Zhang (2011, 2014a) study the role of business and leisure passengers for the incentives to internalize self-imposed congestion, and Verhoef (2017a) studies the design of self-financing mechanisms for congestible facilities with market power. Another branch of the literature has focused on peak-load airport pricing using a model of discrete time with two periods, peak and off-peak, where only the peak period can be congested. In this line, Brueckner (2002), Basso and Zhang (2008) and Czerny and Zhang (2014b) have shown that firms competing in Cournot fashion internalize the self-imposed delays also in the two period framework.

More recently, the dynamics of congestion have been subject to analysis. Silva et al. (2014) proposed a dynamic model of airport congestion, combining the game-theoretic set-up of most of the earlier work with the bottleneck congestion technology proposed by Vickrey (1969) for the analysis of road pricing. Silva et al. (2014) describe monopoly and leader-fringe cases and show that the leader is forced to schedule arrivals according to atomistic patterns in the peak center. They also reported a rather discomforting result, namely that the model seems to have no pure-strategies Nash equilibrium in arrival schedules for the case of a Cournot oligopoly.[1]

Silva et al. (2017) confirmed the non-existence of equilibrium in the described setting for a duopoly, albeit that they demonstrate that it applies only when the so-called value of schedule delay late (γ) exceeds the value of travel delays (α). When the opposite applies, there is an equilibrium; however, it is one in which the strategies are such that no queuing occurs. Although this does not overturn the relevance of the particular case, it does suggest that this would make the model still unable to describe equilibrium on congested facilities with "visible" (queued) congestion. As a consequence, the model would also be unable to provide insights on optimal congestion pricing policies.

Given the widespread prevalence of congestion at airports and the presumed relevance of its dynamic "peak-hour" nature in many instances, combined with the rather extreme nature of leader-fringe competition – the only type of competition that does have an equilibrium in pure strategies with dynamic bottleneck congestion – it is not just an intellectual challenge to characterize a congested equilibrium with firms making decisions simultaneously in a dynamic model of congestion. It is also a task with a clear societal relevance, as the efficiency of regulation (or a lack thereof) has not been assessed in a model with continuous time and travel and schedule delays.

Against that background, this paper investigates whether equilibrium is restored under alternative assumptions on the congestion technology and, if so, whether there is room for implementing optimal congestion pricing. In particular, we believe that the assumptions on the demand side – basically entailing the existence of a most-desired arrival moment and shadow costs of deviations from this moment (β for early arrivals, γ for late ones), and the existence of a disutility of travel delays (with unit value α) – are too reasonable to drop. Although heterogeneity in consumer preferences or in airlines' cost structures may also help to establish equilibrium, it remains a bit awkward that under (too much) homogeneity, no equilibrium would exist. The same is true for uncertainty in travel times. Hence, the specific congestion technology seems a reasonable first candidate alternative assumption to consider.

We build upon the framework set out in Silva et al. (2014), but use a model of flow congestion instead of the bottleneck congestion technology, and focus on simultaneous scheduling by multiple firms. Again borrowing from classics in road congestion modelling, we consider the model originally proposed by Henderson (1974, 1981), and later refined by Chu (1995). The essential feature of the model is that it makes the travel delay associated with an arrival at a certain moment a function of the instantaneous arrival flow at that moment. The model may thus seem to give a reasonable description and approximation of dynamic equilibrium in terms of scheduling behaviour and travel delays when there is no strict and predictable FIFO (first-in-first-out) queuing discipline, and players instead have an unbiased but somewhat rough expectation of the travel delay that an arrival at a certain moment will bring. Another reason why the congestion technology may give a reasonable description of dynamic congestion patterns is when the facility operator has the possibility of opening additional but lower

[1] Daniel (2009) studies in a similar setting the leader-fringe case finding also that the leader is forced to behave atomistically in the center.