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Micro-foundations of congestion and pricing: A game theory perspective

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Abstract

This paper develops congestion theory and congestion pricing theory from its micro-foundations, the interaction of two or more vehicles. Using game theory, with a two-player game it is shown that the emergence of congestion depends on the players' relative valuations of early arrival, late arrival, and journey delay. Congestion pricing can be used as a cooperation mechanism to minimize total costs (if returned to the players). The analysis is then extended to the case of the three-player game, which illustrates congestion as a negative externality imposed on players who do not themselves contribute to it.

Keywords: Game theory; Congestion; Queueing; Traffic flow; Congestion pricing; Road pricing; Value pricing

1. Introduction

Congestion, one of the most frustrating problems in both freight and passenger transportation, vexes policy-makers, while an understanding of the technical foundations of congestion among policy analysts remains weak. Walters (1961) and Mohring (1970) apply microeconomic theory to congestion, but assume aggregate demand functions and take no account of variation in time or schedule delay (i.e. the journey time is the same for all travelers in the peak). Vickery (1969) and

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Arnott et al. (1990, 1993, 1998) among others relax that uniform journey time assumption in the bottleneck model, which takes into account time variation as a factor in congestion, and allows travelers to trade-off journey time for schedule delay (see Lindsey and Verhoef (2000) for a summary). These models are extremely useful, but still consider congestion as a product of many travelers.

Schelling (1978) argues that macroscopic phenomena should be examined from their micro-foundations, the behaviors of individuals. This paper takes that approach, aiming to build the simplest possible congestion model that reflects real phenomena of schedule delays as well as negative congestion externalities. The paper treats congestion as, at its core, a relatively simple phenomenon with a relatively simple solution. This paper considers congestion as comprising multiple interacting players. The departure time decisions of one commuter affect the journey delay and arrival times experienced by other commuters, leading to interactions and possible gains to all players by cooperating. This paper uses the term *journey delay*, or travel time in excess of uncongested times, to contrast with *schedule delay* which refers to the difference in time of departure or arrival compared with preferred conditions. (Other decisions: shifts in mode, route, location, or destination also affect demand of other commuters, but are not included here for clarity of presentation). Game theory, developed by Von Neumann and Morgenstern (1944), presents an analytic approach to explain the choices of multiple actors (agents) in conflict with each other with scope for cooperation, where the payoffs are interdependent (Hargreaves-Heap et al., 1995; Osborne and Rubinstein, 1994; Taylor, 1987). This is distinct from decision theory, where the opponents are states of nature and are passive (Rapoport, 1970). Games are generally classified by the number of players (the games described here are two and three player) and whether the game is zero sum or not. Non-zero sum games engender benefits from cooperation that are absent in zero sum games. Pricing can be a seen as a mechanism to achieve the benefits of cooperation.

The application of game theory requires acceptance of certain assumptions about the behavior of actors and their level of knowledge. First, it is assumed that actors are instrumentally rational. Actors who are instrumentally rational express preferences (which are ordered consistently and obey the property of transitivity) and act to best satisfy those preferences. Here it is assumed that travelers minimize total costs (the sum of congestion journey delay penalties, schedule delay penalties [arriving early or late] and prices).

Second, it is assumed that there is common knowledge of rationality (CKR). Common knowledge of rationality assumes that each actor is instrumentally rational, and that each actor knows that each other actor is instrumentally rational, and that each actor knows that each other actor knows, and so on.

Third, it is assumed that there is a consistent alignment of beliefs (CAB). Each actor, given the same information and circumstances, will make the same decision—no actor should be surprised by what another actor does.

Last, it is assumed all players know the rules of the game, including all possible actions and the payoffs of each for every player. This assumption of perfect knowledge, which runs through traditional route choice and congestion pricing models, is strong, and is realistic only in a simple, highly structured game. This assumption is used for expository purposes here, so that the model does not become too complex. Clearly it would be desirable to extend the model to deal with imperfect information, as discussed in the conclusions, though the extent to which that changes