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Urban travel demand model with endogenous congestion

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ABSTRACT

We formulate and estimate a structural model for travel demand in which users have heterogeneous preferences and make their transport decisions based on network congestion. A key component in the model is the infinite number of users in the network, all of whom have common knowledge about the distribution of preferences in the population. In this setting, the congestion level is endogenously determined in the equilibrium of a game with a continuum of players. For the estimate, we use the first-order conditions of the users' utility maximization problem to derive the likelihood function. For inference, we apply a two-step, semi-parametric method. Using data from Santiago, Chile, we show that the estimated parameters confirm the effect of congestion on individuals' preferences and that demand elasticities obtained by using our framework are consistent with results reported in the literature. We use the model to evaluate the effect on the welfare of increasing the cost of car trips and implementing a second-best fare schedule for bus transit. We also assess the welfare loss caused by congestion in Santiago.

1. Introduction

A challenge of transportation economic analysis is that any policy measure, like road pricing, leads to a new equilibrium in the network. This is, in part, because changes in congestion. Consider, for example, the impact of increasing the fuel price, which creates two opposite and simultaneous effects. On the one hand, car trip demand decreases because of the higher monetary cost of travel. On the other hand, car trip demand increases because of the lower travel time, which results from decreased road congestion. Network equilibrium models explicitly considered these two effects (e.g., Beckmann et al., 1956; De Cea and Fernández, 2001) when assigning flows to the arcs. However, transport policies strongly affect transport demand, which does not include traffic flow reassignment, as well as changes in modal shares and total transport demand.

Demand modeling approaches are used to analyze the impact of transport policies, such as optimal taxation, subsidy, or pricing (e.g., De Borger, 2001; De Borger and Mayeres, 2007; Proost and Van Dender, 2008; Parry and Small, 2009; Ahn, 2009; Wang et al., 2008). In these models, trip demand depends on monetary cost, and average travel time or speed. In turn, these variables depend on the volume of road transport (e.g., car and bus flows). The common practice is to use traffic-type relationships between travel time and demand volume and to introduce this function in the demand model. These travel time functions on traffic flow are estimated separately from the demand model parameters (O'Mahony et al., 1997). This approach may lead to biased results, because of inconsistent estimation of the effects of congestion on travel demand. Moreover, the approach only considers congestion effects on travel time on the users' utility. It neglects any innate aversion to congestion or aversion to pollution produced by congestion.

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This paper proposes a demand model for individual trips per day. The model includes the effects of congestion in a simplified but direct way. It captures the effect of congestion by assuming that the utility of traveling depends on the total travel demand in the transport network. As every user maximizes their utility by choosing the number of trips by mode, the total demand creates an equilibrium among all travelers. The model relies on game theory, as the individual's utility depends on the number of trips made by the other individuals. Each users decision depends on the others decisions. This approach is similar to those used in social interaction models (Brock and Durlauf, 2001).

Since individuals do not know or observe how many trips the other users make, individual decisions are based on the expected number of trips made by others. To estimate this number, we assume that everyone has similar, but not identical, transportation preferences. In particular, the functional form of utility is the same for everyone, with some common parameters. However, since individuals are not identical, preference heterogeneity is represented by idiosyncratic parameters in the utility function. Such idiosyncratic parameters distribute across the population with a probability density function that is known by all individuals. Thus, the individual does not know the others' preferences but can estimate the expected total trips based on a commonly known distribution in the population. This results in a game with an infinite number of players.

More specifically, this demand model is a discrete/continuous choices model (Hanemann, 1984; Dubin and McFadden, 1984) with alternatives that are not perfect substitutes. Indeed, in the estimation sample, individuals use more than one traveling mode during the observation period (one day). For example, for an individual who makes two trips by car and two trips by bus in a day, such modes are not perfect substitutes, since they are not mutually exclusive. The combined use of travel modes maximizes each individual's utility. Therefore, the decisions may not be modeled as a choice between perfect substitutes.

To address this feature, we formulate a utility function that admits corner solutions when it is maximized (Kim et al., 2002). This utility function may represent the preferences of individuals who choose only a subset of the available alternatives. We also assume that only car users cause congestion. Thus, the utility of all road modes of transport is affected by the total car trips.

To estimate the model, our parameterization considers all previously mentioned aspects. Additionally, two parameters represent the unobserved heterogeneity of individuals. One parameter is the intrinsic utility of traveling. Another is the subjective perception of the quality of modes or the taste variation. Assuming a distribution function for these parameters, we formulate a statistical model based on random utility theory. In other words, the error term that appears in random utility models is interpreted as individual heterogeneity. These assumptions allow us to estimate the structural parameters of the utility function. We also prove the existence of a unique equilibrium in the game. This equilibrium characterizes the transport system, given our parameterization.

The main contribution of this paper is the methodology to estimate a travel demand model in which congestion is endogenously determined. This model is suitable for analysis of transport policies, like that of Parry and Small (2009) or Proost and Van Dender (2008), in which the travel demand depends on the congestion level. For instance, our model considers the congestion effect in the computation of the new equilibrium demand level when fuel price changes. This model may also complement network assignment models in the design of area-wide transport policies in which congestion is a concern, such as road pricing.

Another application of the model is measuring the congestion effects in the city. The model allows us to obtain the subjective valuation of congestion, because it enters directly in the utility function and not by means of the effect on travel time. This subjective valuation of congestion may include effects other than travel time increases, such as the valuation of pollution or the discomfort caused by congestion.

The paper is organized as follows. Section 2 presents the basic theoretical model and the parameterization of the utility function based on a discrete/continuous choice model with imperfect substitutes. We also introduce the modeling approach of endogenous congestion and prove the existence and uniqueness of the equilibrium.

Section 3 describes the statistical model. To derive the likelihood function, we use the first-order condition of the individuals utility maximization problem (Kim et al., 2002). The random components in utility are associated to the intrinsic utility of traveling and quality perception of the modes. By specifying a distribution function for these components, we obtain an econometric model that is consistent with the microeconomic model. We also study the model identification and conclude that the structural parameters of the model are identified because of the nonlinearity of the utility function. Section 3 also presents the estimation procedure, which is based on a two-step semiparametric method (Bajari et al., 2010; Bisini et al., 2011). In the first step, the expected number of car trips of equilibrium, conditional on the price, is estimated nonparametrically. In the second step, the likelihood function on the structural parameters is maximized using the nonparametric estimate from the previous step as an independent variable.

Section 4 reports the results of the estimated model using data from Santiago de Chile. We find that transportation demand exhibits low price elasticity and a significant congestion effect.

Section 5 presents the application of the model to evaluate the impact of two policies: increased cost of car travel and second-best fare for bus transit. The model also assesses the loss of welfare caused by the congestion effect on the users utility.

Finally, we conclude and discuss possible extensions of the model in Section 6.