MAR10-2009-000428

Abstract for an Invited Paper
for the MAR10 Meeting of
the American Physical Society

The Physics of Traffic Congestion and Road Pricing in Transportation Planning

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This presentation 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. A multi-agent model of travelers competing to utilize a roadway in time and space is presented. To realize the spillover effect among travelers, N-player games are constructed in which the strategy set includes N+1 strategies. We solve the N-player game (for N = 7) and find Nash equilibria if they exist. This model is compared to the bottleneck model. The results of numerical simulation show that the two models yield identical results in terms of lowest total costs and marginal costs when a social optimum exists. Moving from temporal dynamics to spatial complexity, using consistent agent- based techniques, we model the decision-making processes of users and infrastructure owner/operators to explore the welfare consequence of price competition, capacity choice, and product differentiation on congested transportation networks. Component models include: (1) An agent-based travel demand model wherein each traveler has learning capabilities and unique characteristics (e.g. value of time); (2) Econometric facility provision cost models; and (3) Representations of road authorities making pricing and capacity decisions. Different from small-network equilibrium models in prior literature, this agent- based model is applicable to pricing and investment analyses on large complex networks. The subsequent economic analysis focuses on the source, evolution, measurement, and impact of product differentiation with heterogeneous users on a mixed ownership network (with tolled and untolled roads). Two types of product differentiation in the presence of toll roads, path differentiation and space differentiation, are defined and measured for a base case and several variants with different types of price and capacity competition and with various degrees of user heterogeneity. The findings favor a fixed-rate road pricing policy compared to complete pricing freedom on toll roads. It is also shown that the relationship between net social benefit and user heterogeneity is not monotonic on a complex network with toll roads.