Journal of Operations Management 39-40 (2015) 31–47

Contents lists available at ScienceDirect

Journal of Operations Management

journal homepage: www.elsevier.com/locate/jom

Cost-sharing in directed networks: Experimental study of equilibrium choice and system dynamics

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A R T I C L E I N F O

Article history:
Available online 26 July 2015

Accepted by Daniel. R. Guide

Keywords:
Cost-sharing
System dynamics
Positive externalities
Experiment

A B S T R A C T

This study reports the results of an experiment on directed networks with positive externalities induced by cost-sharing. Subjects participated in a network game in which they had to choose between private and public transportations. If a player chose public transportation, then she shared the travel cost equally with other players making the same choice, whereas if she chose private transportation, then her travel cost was fixed. Travel costs on the private route were manipulated across the two experimental conditions. In one condition, these costs were homogeneous among players; in the other condition, they were heterogeneous among players and only privately known. We found that half (none) of the player groups in the homogeneous (heterogeneous) condition converged toward the efficient equilibrium. Examination of the system dynamics shows that convergence toward efficiency was facilitated by: (1) the existence of an intermediate equilibrium choice; and (2) strategic teaching by which a farsighted player chooses strategies with poor short-term payoff in order to shift group decisions to the efficient equilibrium and thereby increase her own long-term benefit.

1. Introduction

Transportation networks provide the foundation for the movement of people and goods across space and time, and are essential to the functioning of modern societies. The design and control of such networks requires thorough understanding of fundamental physical, behavioral, and social issues that are major research topics in the management, transportation research, economics, and computer sciences. Focusing on cost-sharing in directed networks, our study is positioned at the intersection of these disciplines.

In many settings in transportation networks, the overall behavior of the system is a complex product of the actions of multiple independent agents (e.g., drivers, commuters, etc) who can generally be labeled as network users. These agents typically attempt to optimize their objective functions with no regard for the welfare of others. The externalities resulting from the decisions of each user *are negative* if individual benefits are a decreasing function of the number of other group members making similar choices. Examples include choice of routes in congestible networks (Cominetti et al., 2006, 2009; Correa and Stier-Moses, 2011; Rapoport et al., 2009, 2014; Mak et al., 2015), and choice of time of departure in directed traffic networks with multiple bottlenecks (Daniel et al., 2009). In many other settings, the externalities are positive, as when the benefit of a choice of route is an increasing function of the number of other users making the same choice. This could happen, for example, when users of the same mode of transportation share the travel cost, as could happen with carpool and shuttle taxi. Previous experimental research on interactive decision behavior in networks (e.g., Daniel et al., 2009; Gisches and Rapoport, 2012; Mak et al., 2015; Morgan et al., 2009; Rapoport et al., 2006, 2009, 2014; Selten et al., 2007) has focused on network games with negative externalities. In contrast, ours is the first experimental study of cost-sharing in traffic network games with positive externalities.

Our study is particularly concerned with whether – and if so, how – network users might achieve collectively the efficient (socially optimal) Nash equilibrium through repeated play of a cost-sharing network game when the stage game has Pareto rankable equilibria. The socially optimal equilibrium may naturally be viewed as the optimal outcome subject to the constraint that the solution is “stable” in the sense that no agent has an incentive to unilaterally deviate from it once it is proposed (e.g., by a network

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http://dx.doi.org/10.1016/j.jom.2015.07.004

designer) or, alternatively, reached by some process of adaptive learning. Our findings show that the likelihood of subjects converging toward the efficient equilibrium depends crucially on whether the payoff functions are common knowledge. In Condition Homogeneous, where travel costs were the same and commonly known among users, half of the groups converged toward the socially efficient equilibrium. In Condition Heterogeneous, where the variable travel cost of private transportation was only privately known, nine of the ten groups converged toward the inefficient equilibrium. We further suggest that convergence toward efficiency was facilitated by: (1) the existence of an intermediate equilibrium choice, and; (2) strategic teaching by which farsighted (sophisticated) players made route choices that significantly decreased their short-run payoff in order to signal their willingness to join public transportation and thereby achieve long-run benefits. These signals could facilitate the migration of the route choices of other group members over iterations of the stage game toward the efficient equilibrium.

We place special emphasis on the dynamics of play, in particular dynamics that converge to socially optimal outcomes (see, e.g., Balcan et al., 2013; Charikar et al., 2008). We note that when experimental games are iterated in time, players may change their behavior over iterations, exhibiting behavior that simultaneously depends on their growing understanding of the structure of the game and on revisions of their beliefs about future behavior of other players in the system. Most of the previous literature attempted to explain the dynamics of play in experimental games in terms of reinforcement learning, belief learning, regret minimization, and best-response behavior (cf. Balcan, 2011; Balcan et al., 2013; Camerer 2003; Chapter 6; Erev et al., 2010; Nisan et al., 2007; among other examples). As noted by Balcan et al. (2013), these learning models are myopic and therefore do not fully capture the information that the players may have prior to the game or possibly acquire during the game about its overall structure, or the farsighted behavior of the users when the stage game is iterated in time. Balcan et al. (2013) mention two barriers to simple dynamics performing well in accounting for decision behavior. The first is computational; we do not know how convergence to some outcome, if reached at all, depends on the particular parameters of the experiment. The second barrier is incentive-based. Even if an efficient solution is known by the players, there is the issue of whether the players would individually be willing to play it. This may depend on the beliefs that the players acquired in previous periods about the rationality of the other players, the strategies that other players may be expected to employ in the future, and the degree that other players may be trusted to adhere to tacit agreements if, indeed, they have been reached. Moreover, to gain tractability, existing models often assume homogenous agents, whereas the experimental literature on repeated interactive behavior in large groups presents ample evidence for considerable individual differences (e.g., Gisches and Rapoport, 2012; Selten et al., 2007). Our perspective is that if a network game has multiple equilibria that are Pareto rankable, as in our study, then players have the option of sending signals, frequently at a high short-term cost to themselves, about their intention to shift group behavior from an inferior equilibrium to a more efficient equilibrium. We later refer to such behavior as strategic teaching. Some players may intrinsically be more inclined to send such signals than others. Depending on their number, these players may be critical in the convergence of the group toward an efficient outcome. We shall be reporting evidence in support of this kind of dynamics.

The rest of the paper is organized as follows. Section 2 outlines the theoretical background of fair cost-sharing allocation mechanism that we employed in our experiment and the general design of our experiment. Section 3 reviews recent relevant literature on route choice. Section 4 describes the experiment. Sections 5 and 6 report the results of the experiment, including basic data analysis followed by in-depth analysis of the dynamics of play. We conclude the paper with Section 7, which includes further discussion of our findings and proposes ideas for future research.

2. Theoretical background and general experimental design

2.1. Fair cost-sharing allocation mechanisms

A cost-sharing allocation mechanism may be viewed as the underlying protocol of play that determines how much a network that serves multiple users will cost to each of them. Theoretical research in this area has been mostly conducted by computer scientists interested in communication networks (e.g., Anshelevich et al., 2003, 2008; Balcan et al., 2013; Harks and Miller 2011). In the simplest protocol, each user i, $i = 1, 2, .., k$, has a pair of nodes (O_i, D_i) in a directed graph that she wishes to connect. She does so by choosing a path S_i that originates at O_i and terminates at D_i. The cost-sharing allocation mechanism then charges user i a cost of $C_i(S_1, S_2, \ldots, S_k)$, implying that the cost of user i may depend on the choice of paths by the other users. In our experiment, we focus on a very natural allocation mechanism where the cost of each edge is shared equally by all the users whose paths contain it. That is:

$$C_i(S_1, S_2, \ldots, S_k) = \sum_{e \in S_i} \frac{c_e}{\left|\{j : e \in S_j\}\right|},$$

where c_e is the cost associated with traversing edge e and $|x|$ is the number of elements in set x. This equal ("fair") cost-sharing allocation mechanism can be rationalized by economic theorizing in the following ways: (1) it can be derived from the Shapley value, possibly the best known solution concept for cooperative games (cf. the theoretical discussion in Moulin and Shenker, 2001; Chen and Roughgarden, 2009); and (2) it can be shown to be the unique cost-sharing scheme that satisfies a set of different axioms (see Feigenbaum et al., 2001; Herzog et al., 1997). The sum of the costs in the union of all paths S_i, is completely paid for by the users under this mechanism:

$$\Sigma_{i=1}^{k} C_i(S_1, S_2, \ldots, S_k) = \sum_{e \in \cup_i S_i} c_e.$$

In our experimental setup, we take the fair cost-sharing allocation mechanism as given, and study behavioral route choices in anticipation of the fact that travelers on the same route would end up sharing costs equally. The cost-sharing stage, in the context of our experimental setup, may therefore be seen as a sequential game's final stage that was not actually played by the subjects, while the cooperative- solution-based outcome of that stage determines the functional forms of the game payoffs.

2.1.1. Example

Following examples in Anshelevich et al. (2008) and Roughgarden and Tardos (2007), consider a directed network with k players. All the players share the same destination D, but each player i starts from her specific origin O_i. Each player may choose a private path $(O_i \rightarrow D)$ and incur the cost of travel $1/i$. This choice and its outcome are not affected by the choices of other group members. Alternatively, player i may choose the public path $(O_i \rightarrow V \rightarrow D)$ and incur the endogenously determined cost $(1 + \epsilon)/m$, where $\epsilon > 0$ is arbitrarily small, and m $(1 \leq m \leq k)$ is the number of players choosing this path. We assume that decisions are made in the order 1, 2, …, k, and that each player is fully informed of the decisions made by the players who precede her in the sequence. It is to the benefit of all the k players to choose the public path