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Three-player game-theoretic model over a freight transportation network

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Abstract

With recent development in freight transportation industry, its network structure has become more complicated, as many decision-makers competing for profits with each other are involved. While most recent research in this area is focused on the perfectly competitive market and the prices are given as a constant tariff rate, little attention has been paid to the system optimization problem in the absence of regulatory authority. In this paper, we investigate the competitive equilibrium in an oligopolistic market on a freight network. A partially non-cooperative game among shippers, carriers and infrastructure companies (IC) is examined. All three kinds of players act as profit maximizing agents, except that the carriers and ICs are assumed to behave cooperatively in their own coalitions. We consider the vertically efficient nonlinear tariff schedules which are commonly used in the transportation industry. By introducing a three-stage game-theoretic model, we show that the equilibrium flows can also maximize total system profits if the IC and the carrier both use vertically efficient nonlinear pricing schedules. The division of the surplus associated with each shipment is obtained by solving a linear programming problem. We provide a few examples under different situations to show the existence of the resulting equilibrium.

Keywords: Nonlinear tariff; Freight network equilibrium; Profit maximization; Non-cooperative game

1. Introduction

The Freight Network Equilibrium Problem (FNEP) has attracted a lot of attention over the past two decades, but most previous studies involve two agents only: the shipper and the carrier. Typically, a simultaneous shipper–carrier equilibrium for the FNEP can be formulated in the following way: the shipper, or so called the manufacturer, controls a set of origin-to-destination shipments, with the demand for each shipment decided by an inverse demand function. To get the shipments to the market, the shipper must use a carrier or coalition of carriers who control not only the conveyance but also the transportation infrastructure. The shipper selects an output while the carriers charge shipper a freight rate obtained by maximizing their own profits. With such

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a setting, a game theoretical approach can be applied to formulate and analyze FNEP. In general, two kinds of alternative objectives are used to describe the agents' behavior: User Equilibrium (UE) or System Optimum (SO) (Harker, 1987, 1988). In Hurley and Petersen (1994), UE principle is used to model shipper's behavior and the carrier is assumed to behave according to the SO principle; by using a particular form of nonlinear tariff, they showed that the UE and SO can be simultaneously satisfied in an incomplete market. Very recently, game-theoretical approaches were also employed to investigate other aspects of the FNEP. Bassanini et al. (2002) examined railroad capacity allocation and track time pricing; Castelli et al. (2004) considered a strategic game between two players acting on the same road transportation network, where the first player aims at minimizing transportation costs, whereas the second player aims at maximizing profit.

However, in recent years the freight industry throughout the world is in a process of restructuring and commercialization. Regulations are designed to liberalize the market for providing transportation service and enhance competition within the sector. The restructuring has normally involved the separation of the infrastructure from operations. People expect that this would result in both the rational distribution of the resources and increased efficiency in service provision. In general, the freight industry in the future can be considered to comprise three types of agents: the shipper, the carrier and the infrastructure company (IC). When the system involves more than two players in a hierarchical game, the computation of equilibrium is incomparably more difficult (Basar and Olsder, 1999). To simplify the problem, Nagurney (1999) and Nagurney et al. (2001) used a fully decentralized model to formulate and solve the FNEP using a variational inequality approach. Nevertheless, when different players are in asymmetric positions, their models are difficult to analyze the interactions among the players with different objective functions, and with the model the planner can hardly manage with the goal of system optimization through appropriate form of tariff. The difficulty of such problems is that when the freight industry moves to a pure market economy, we must face the situation wherein each one of the players has the ability to enforce his or her decision on the other players who reacts independently and rationally.

Our approach, in contrast, provides a different point of view. We develop a competitive equilibrium model for three types of players (one shipper, multiple carriers and multiple ICs) in either symmetric or asymmetric positions, each acting as profit maximizing agents. In order to gain an SO solution, we restrict the carriers and ICs to two-part tariffs, which has a general form: $R(x) = b + ax$, where x is the total shipment. In our analysis, under the oligopoly equilibria, parameter "a" will be set to the players' marginal costs and parameter "b" affects a profit distribution between the players. Without loss of generality, we consider a three-stage sequential decision process. First, the ICs decide a tariff to the carriers, according to their own cost function and the information they have about the shipper and the carriers. Then, the carriers determine another tariff to the shipper, according to their own cost function, the tariff given by the ICs, and the information they have about the shipper. Finally, the shipper decides the quantity of the production to maximize its own profit. In each stage, we refer the agent who gives the tariff to as an "upper level" agent, and correspondingly, the agent who accepts the tariff as a "lower level" agent. On one side, the carriers and ICs have a choice of parameters, "a" and "b", of the tariff. On the other side, when there are multiple carriers and ICs, the shipper can freely choose which carrier to transmit shipment and the carrier can freely choose the ICs. In terms of game theory, the problem of interest can be considered as a strengthening of the Nash equilibrium known as subgame perfect Nash equilibrium. The central idea underlying this concept is the principle of sequential rationality: equilibrium strategies should specify optimal behavior from any point in the game onward (Mas-Colell et al., 1995), which means, in this model, each agent will choose its own profit-maximizing strategy, given the "upper level" agents' strategies and "lower level" agents' information. Since it is a finite game of perfect information, we can thus apply the idea of backward induction: determining the optimal actions sequentially for moves at the final decisions at each stage. We show that in this game, by using the nonlinear tariff, the equilibria of the Nash equilibrium is also the system optimum. Furthermore, the model predicts the set of tariff schedule of the carriers and ICs and provides a division of surplus among the players.

The paper is structured as follows. Section 2 contains a simple example with one shipper, one carrier and one IC. A three-player non-cooperative game between the three agents is analyzed step by step. The model results in a vertically efficient flow which is also an equilibrium. In Section 3, the example is extended to include competition among multiple ICs. We introduce an n-person cooperative cost-saving game, and show that the model leads to an equilibrium. In Section 4, we offer a more general equilibrium result by considering