論文 / 著書情報
Article / Book Information

題目(和文)	単一ボトルネックネットワークでの通行権取引制度導入によるパレート改善
Title(English)	Pareto-Improving Pricing Based on Tradable Bottleneck Permits Scheme for Managing Congestion at a Single Bottleneck
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出典(和文)	学位:博士（工学）, 学位授与機関:東京工業大学, 報告番号:甲第9979号, 授与年月日:2015年9月25日, 学位の種別:課程博士, 審査員:朝倉　康夫,屋井　鉄雄,福田　大輔,室町　泰徳,花岡　伸也,赤松 隆
Citation(English)	Degree:, Conferring organization: Tokyo Institute of Technology, Report number:甲第9979号, Conferred date:2015/9/25, Degree Type:Course doctor, Examiner:,,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	要約
Type(English)	Outline

Pareto-Improving Pricing Based on Tradable Bottleneck Permits Scheme for Managing Congestion at a Single Bottleneck

by

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A Dissertation

Submitted to the Department of Civil Engineering

in partial fulfillment of the requirements for the degree of

Doctor of Engineering

at the

Tokyo Institute of Technology

Abstract

The Tradable bottleneck permits (TBP) scheme is proposed as one of the first-best time-varying pricing schemes and has been shown to be able to minimize social cost. In order to resolve a congestion problem during morning rush hour in a corridor with a single bottleneck, the scheme provides these functions as follows: (i) a road administrator issues permits that allow the holders to pass through the bottleneck at a pre-specified time period ("bottleneck permits") and (ii) a new trading market is established for bottleneck permits valid for a pre-specified time period.

Although the most effective state from the aspect of social cost minimization can be realized by applying the TBP scheme, a Pareto improvement is not always achieved, which means that the scheme may harm some drivers. Then, the harmed drivers must be strongly against the TBP scheme, even if it can minimize the total cost of all drivers.

The objective of this dissertation is to reveal the situations in which the TBP scheme does not always achieve a Pareto improvement when a target network has a single bottleneck and to design Pareto-improving tradable bottleneck permits schemes. This study focuses on two situations: first, the network has a merge point, and second, there is heterogeneity in marginal utility of toll payment among drivers.

In order to consider the framework of time-varying congestion pricing, departure time choice models are reviewed. In the model, drivers' behavior is defined by the tradeoff between waiting delay at bottleneck and schedule delay, which is the difference between desired arrival time and actual arrival time. In order to represent the waiting delay at bottleneck, deterministic description of delay with cumulative numbers of drivers is employed. In the first proposed model (Vickrey, 1969), the objective function for drivers to minimize is trip cost which consists of cost of waiting delay, schedule delay, and toll payment. We arrange the model in utility base. When the reluctance to pay toll charge is homogeneous among drivers, money-metric utility is employed. Otherwise, time-based utility, which is standardized to the unit of waiting delay, is employed.

We show that the first-best pricing scheme under tradable bottleneck permits for Y-shaped network is not always Pareto improving, and the money-metric utility of one

group of drivers is increased by the permit pricing, a phenomenon akin to the bottleneck paradox. Therefore, we propose three implementations of TBP scheme for Pareto-improving pricing: (i) a merging priority rule is included in the TBP scheme by creating a different market for each origin; (ii) the TBP revenues are refunded as monetary compensation to drivers whose utility is decreased; and (iii) the permit revenues are used to expand bottleneck capacity. We derive the equilibrium solutions for each implementation and demonstrate that a Pareto improvement is achieved and social cost is decreased by using the permit revenues for expanding the bottleneck capacity.

For the other situation in which Pareto improvement is not achieved, we show the time-dependent utility of drivers when they have different schedule flexibility and reluctance to pay toll charge. The cases with and without TBP scheme are compared analytically. Then, we propose the TBP scheme that achieves a Pareto improvement without a road administrator refunding the revenues to drivers. In order to discuss the case in which there exists heterogeneity in schedule flexibility and marginal utility of toll cost, we focus on a one-to-one network with a single bottleneck and employ a departure time choice model in which drivers choose their arrival time depending on time-based utility. We assume two classes for two attributes as heterogeneity “busy/free” and “rich/poor” and formulate the drivers’ utility changes caused by implementation of TBP. In this assumption, we show that a Pareto improvement is not achieved, and the utility of “busy–poor” drivers is decreased by the effect of the TBP scheme. We propose partial implementation of TBP as a scheme for a Pareto improvement. In this partial TBP scheme, the bottleneck capacity is assigned to drivers with and without a bottleneck permit, where the driver who has a bottleneck permit can pass through the bottleneck without congestion and a driver without it experiences congestion. As a result, we reveal conditions for the amount of the bottleneck permits that can satisfy a Pareto improvement. Finally, this study finally discusses the requirements for a Pareto improvement that are derived by the proportion of the amount of issued bottleneck permits, the number of each class driver, and the gap between the classes.