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Green transportation implementation through distance-based road pricing

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ABSTRACT

The implementation of electronic toll collection (ETC) over freeways not only enables nonstop traffic flows through toll collection zones but also facilitates more flexible schemes for road pricing, such as distance-based and time-based schemes, as both the on-ramp and off-ramp time stamps of a trip can be detected. Based on such an ETC environment, this study develops a road pricing model which considers the perspectives of road users, the government, and the ETC agent, seeking to attain greener transportation by leveraging the external costs related to environmental impact and accident potential. Thereupon, a Green Safety Indicator (GSI) is proposed to comprehensively account for the service level of freeway traffic. The optimal solution for the benefits generated from three scenarios are determined against GSI-based equilibria, which can maintain the revenue for the government, offer the ETC agent higher profits, and allow road users off-peak discounts, thereby promoting a tripartite win–win situation among stakeholders.

1. Introduction

The Electronic Toll Collection (ETC) system with varying toll rates over different time slots was introduced to SR91 in 1995. It was the first ETC system that implemented dynamic road pricing in the United States. Its toll rates originally ranged from US$ 0.25 to US$ 2.5 in December 1995, and later rose to the range from US$ 1 to US$ 4.75 in 2002. The toll was levied in accordance with directional traffic volumes. Accordingly, the highest toll rate was applied for the afternoon peak hours (around the period during 3 p.m. and 5 p.m.) of weekdays, while the toll was at its lowest from around 10 p.m. to 7 a.m. every day.

The Electronic Road Pricing (ERP) system in Singapore is another well-known case, which successfully addresses traffic congestion by using a more flexible dynamic pricing scheme. It has assessed the reasonability of toll rates once every three months since September 1998, and the assessments are made based on the observations of traffic speeds and trends of half-hourly average speed in ERP zones. In addition, “stepped tolls” are employed to prevent road users from deliberately decreasing or increasing their speed to save tolls, and are adjusted in a half-hourly basis in response to the ERP roadway assessment. For example, given the target speed of 45–65 km/h for a half-hour period, if the average speed is below 45 km/h, then the ERP toll will be increased for the period. Conversely, if the average speed exceeds 65 km/h, some discount on the ERP toll will be granted.

The distance-based ETC system has been broadly adopted due to the technology that allows multi-lane free-flow ETC; toll collection zones can be set over freeway mainlines (between two ramps), and thereby both the on-ramp and off-ramp time stamps of a

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trip can be recorded. France, Canada, Australia, Japan, and South Korea have recently implemented distance-based ETC systems, where the toll for a trip is primarily based on its mileage on the freeway but also considers factors such as time slots, vehicle types, special roads/areas, and exhaust emissions. Essentially, the United States, Canada, Australia, and Singapore use dynamic models for toll rates on some of their turnpikes, where basic toll rates are employed, while dynamic toll adjustments are further imposed for relevant considerations. Canada and Australia modulate the adjustments of toll rates mainly based on the price index. On the other hand, Singapore and the United States leverage toll rates for regulating traffic flows, particularly with respect to flow speed; when a turnpike is congested, the toll rate is increased.

According to the aforementioned real-life cases of time-based road pricing schemes and relevant literature (Lu, 2013; Wang et al., 2011), to deal with the problem of congestion pricing, it is necessary to define the scope of the study firstly, which can be a particular corridor, a road with some specific alternative paths, or a network. Secondly, the demand function, cost function, and objective function to implement congestion pricing for the defined scope have to be formulated. Thereupon, a pricing method is to be chosen; commonly used methods for congestion pricing include marginal cost pricing, sub-optimal pricing, profit maximization method, and double planning method.

Other than the purpose of traffic control and the consideration of financial management of ETC operation, to more comprehensively reflect external costs of using roads in different traffic conditions has been the emerging concern for highway management, in light of the trend to foster green transportation. Hence, this study proposes a Green Safety Indicator (GSI) for evaluating traffic levels of service inclusively based on flow efficiency, environmental impact and accident potential as well. Further, GSI is incorporated into the problem of distance-based road pricing, which explicitly factors the competition and interaction between traffic-related stakeholders, primarily including the government, road users, and the ETC agent as the third partner entrusted by the government. Accordingly, the pricing scheme is designed, seeking to reach the system equilibrium associated with the optimal solution and compromise variant objectives from the perspectives of stakeholders as follows (Chang and Jiang, 2007):

1. Road users: after the implementation of the ETC system based on mileage, toll fees are calculated based on how much it costs to reduce the number of kilometers. Road users consider the use of the highway with respect to mileage, total tolls payable, and the quality of service, namely:
   - Toll rates and total collection.
   - Traffic level of service: whether traffic is smooth or congested.
2. The Government – Highways Agency: The National Freeway Bureau, as the highway management authority generally has the following specific objectives:
   - To maximize traffic volumes through overall operational efficiency optimization of the road network system.
   - To minimize the negative effect on the system operation and the total cost of social and environmental impact.
   - To enhance traffic safety and provide related regulation rules.
   - To maintain the newly-constructed freeways and ensure that the freeway maintenance has a reasonable source of income.
3. The ETC agent: the perspective of the agent plays a critical role in this research, as it is an enterprise with clear business objectives:
   - To maximize the number of toll collection services when traffic demand is at its greatest.
   - To earn the maximum profits.

This research develops distance-based and GSI-based road pricing models in both static and dynamic contexts. We also create a case study based on the ETC system in Taiwan to illustrate concepts and mathematics of the developed models. Taiwan government completed the construction of a per-entry-based ETC system by 2005, and it began operating on February 10, 2006. Later, a distance-based system that enables multi-lane free flow (nonstop) traffic through toll collection zones was introduced on December 30, 2013. For sustainable operation, the government collects NT$ 22 billion in fees per year from road users (New Taiwan Dollars, NT$, the unit of currency used throughout this paper). However, a regulation policy also allows free-of-charge travel for 20 km per car per day for local commuting traffic. Upon these two authorization conditions, we adopt profit maximization from the aforementioned pricing methods, as it enables the consideration of the need to maintain financial stability and the policy of the 20-km range for free usage.

In the next section, we first introduce the proposed modeling schemes for distance-based road pricing in both static and dynamic contexts. GIS and the modeling issues related to each stakeholder are also detailed in this section. Section 3 presents the development of the pricing models and their implementation on the ETC system in Taiwan. Concluding comments are provided in Section 4, which highlight the research findings and practical insights of this study.

2. Pricing modeling scheme

2.1. Static road pricing model

Road pricing in this study utilizes the principle of equity of users and sustainable finances for maintenance. As stated, the Taiwan Area National Freeway Bureau (TANFB) has to keep 22 billion Taiwan dollars per year for the highway maintenance foundation, while providing 20 km free-of-charge travel per car per day. With these two conditions, the pricing can be formulated as Eq. (1):

$$W^* = \sum_{O,D} (N_{PC}^{O,D} P_{PC} + N_{HV}^{O,D} P_{HV})(L_{O,D} - 20)$$
$$\text{Subject to } W^* = 22{,}000{,}000{,}000 \tag{1}$$