Impacts of pavement deterioration and maintenance cost on Pareto-efficient contracts for highway franchising

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\textbf{ABSTRACT}

In a build-operate-transfer (BOT) highway project, pavement roughness progression generally has a direct impact on the highway maintenance cost and user costs. Given two common rehabilitation strategies, this study respectively investigates the optimally designed highway capacity and tolls of multi-type vehicles in Pareto-efficient contracts. Under supplementary conditions, it proves that the optimal toll revenue could fully cover the highway construction and maintenance cost in these contracts, no matter with or without the regulated traffic composition. Further extensions are made to evaluate and identify properties of the highway v/c ratio, rehabilitation period or critical roughness under the two rehabilitation strategies, respectively.

\section{1. Introduction}

In recent years, rapid economic expansion and traffic demand increase require the massive development of intercity highways, which adds a heavy economic burden to the government. Many governments began privatizing transportation infrastructures, since people believe that private projects have the advantage of "efficient gains, private financing, and better identification of attractive investment projects". Among these public-private partnership (PPP) projects, the build-operate-transfer (BOT) contract is generally utilized by many intercity highway projects. In such a project, the private firms who have won the government bidding need to build a highway at its own expense firstly, and then collect tolls from users to cover its investment and profit over a concession period. At end of this period, the private firms need to transfer the highway to the government. Overall, given the enormous amount of money spent on building, maintaining and operating highways, many project operators are seeking an appropriate basis to optimize the tradeoffs between their investment and economic benefit obtained by highway users. As a result, for these BOT highway contracts, it is critical to identify the optimal toll charges and highway capacity from their predictive economic models, which could lead to the an efficient outcome for the government and private firm that "neither the social welfare nor private profit could be further enhanced without reducing the other" (Tan et al., 2010).

With regard to the project investment cost, it mainly includes the highway construction and maintenance costs, which are primarily determined and reflected by the highway capacity and pavement serviceability (Small et al., 1989). Theoretically, the highway capacity is defined as the maximum traffic volume per unit period and directly related with pavement width, while the pavement serviceability is widely denoted by the pavement roughness\textsuperscript{1} in highway engineering studies (Paterson, 1987). Considerable studies assumed the highway construction cost is a function of highway capacity (Keeler and Small, 1977; Tan et al., 2010; Small et al., 1989). Among these works, Paterson (1987) and Small et al. (1989) introduced the concept of Pavement Roughness Index (PRI), which is defined as a ratio of the pavement surface roughness and pavement thickness. The PRI is a measure of the pavement surface roughness and can be used to predict the cost of pavement rehabilitation projects.

\textsuperscript{1} Pavement roughness is a measure of the irregularities in the pavement surface, and draws together the impacts of all other pavement stress (e.g. cracking, rutting, disintegration, potholes, and deformation).

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In addition, the pavement maintenance cost, especially the periodic rehabilitation expenditure, serves as the main investment to ensure the acceptable pavement serviceability for highway users. More specifically, Fwa (2006) emphasized that the rehabilitation maintenance cost accounts for about 25–40% of the highway initial construction cost. However, in the technical and fiscal estimation studies, it is often roughly estimated as a part of the highway capacity investment cost. The rough estimation of maintenance cost, especially by neglecting the effects of traffic demand and composition on pavement deterioration progression, may lead to a great variation with the actual pavement maintenance cost (Verhoef and Mohring, 2009). Therefore, this study aims to analyze the properties of BOT highway contracts under the impacts of pavement deterioration and maintenance cost.

1.1. Relevant studies

In the analyses of economic issues for highway franchising, most traffic economists analyzed the properties of BOT contracts from aspects of government and private firms, by ignoring the impact of pavement deterioration and maintenance cost. One important achievement of these studies is the self-financing theorem, which points out that the optimal toll charge is equal to the difference between the marginal social cost and marginal private cost of a trip, and the toll revenue could exactly cover the highway investment cost under some basic first-best toll conditions (Guo and Yang, 2009a; Keeler and Small, 1977; Mohring and Harwitz, 1962; Newberry, 1988, 1989; Verhoef and Mohring, 2009; Yang and Meng, 2002). Another well-known founding derived from economic analyses is the constant volume-capacity (v/c) ratio property, which reveals that the profit-maximizing firms would offer the same congestion service level with the welfare-maximizing government under certain conventional assumptions (Spence, 1975; Xiao et al., 2007). Tan et al. (2010) further demonstrated that the optimal v/c ratio for any Pareto-efficient contract is constant along the Pareto-optimal frontier and is equal to the socially optimal v/c ratio. However, no study has analyzed whether the above mentioned achievement and well-known findings still hold while taking the pavement maintenance cost into consideration.

Meanwhile, traffic engineers eventually realized the importance of pavement roughness progression to the estimation of highway maintenance cost and user costs. To optimize the pavement rehabilitation strategies, they utilized the life-cycle cost to analyze the tradeoff between the pavement maintenance cost of highway operators and the road-wear cost of users. Note that the users’ road-wear cost mainly includes the costs of vehicle repair, depreciation, and fuel consumption, which is directly related to the pavement roughness. In general, the approaches of studying rehabilitant strategies in previous literature can be classified into three major categories: optimal control theoretical approaches (Friesz and Fernandez, 1979; Markow and Balta, 1985; Rashid and Tsunokawa, 2012; Tsunokawa and Schofer, 1994), optimization mathematical programming approaches (Gu et al., 2012; Lee and Madanat, 2014; Li and Madanat, 2002; Moreno-Quintero et al., 2013; Newberry, 1989; Ouyang and Madanat, 2004; Yin et al., 2008), and statistical approaches (GEIPOT, 1982; Hodges et al., 1975; Paterson, 1987). To sum up, these approaches mostly predetermined the project factors of toll charges, traffic demand and capacity to optimize the highway pavement rehabilitation strategies.

However, among these engineering and economic studies, most of them ignored the fact that the traffic demand and maintenance cost always interact with each other in practice. As we have mentioned, traffic demand is considerably affected by highway user cost, including the toll charge, travel time cost, and road-wear cost. On the contrary, the pavement roughness and maintenance investment cost are also affected by the traffic demand and traffic composition. As Fig. 1 illustrates, Paterson (1987) presented an example of the progression of pavement roughness, under pavement structure number\(^2\) $SN = 5$. It reveals that under the given pavement strength, the roughness shows diverse increasing trends under different growth rates of traffic loading, which is directly determined by the

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Fig. 1. Pavement roughness progression prediction for six constant annual traffic loading estimates (Paterson, 1987).

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\(^2\) Pavement strength parameter is used to predict on the principle of loading–spreading or stress-distribution. The modified structure number is adopted by AASHTO to represent pavement strength, which is calculated by summing the thickness of pavement layers weighted by material-layer strength coefficients (Paterson, 1987, Page 135–143; GEIPOT, 1982).
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