Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 9 (2015) 130 – 148

Transportation Research Procedia

www.elsevier.com/locate/procedia

21st International Symposium on Transportation and Traffic Theory

Optimal Urban Development Density along A Multi-Modal Linear Travel Corridor with Time-distance Toll Scheme

David Z.W. Wang *, Bo Du

School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

Abstract

Consider a travel corridor with a multi-modal transport system (i.e., highway and railway) that connects a continuum of residential locations to a point of CBD. Both highway and railway are subject to congestion effects. All commuters travel along the corridor from home to work in the morning peak hour. The travel costs include travel time, schedule delay and monetary cost. The spatial dynamics of the traffic congestion on both transportation systems are determined by the trip-timing condition, that no traveler will experience a lower travel cost by departing at a different time or switching to a different mode. The flow dynamics on the highway will be considered by applying basic LWR model, while crowdedness (i.e., passenger density on the train) is used to describe the congestion on the railway. The simultaneous temporal and spatial dynamics of commute traffic pattern will be modeled by applying a second-order partial differential complementarity system approach. A time-distance road pricing scheme is applied to achieve the system optimal condition. The urban population is assumed to be located continuously along the corridor. However, the spatial population density distribution is regarded as variant. As is well known that the urban planning issue of population density distribution affects the transportation system significantly, this study aims to find the optimal urban population density distribution in a linear continuous travel corridor leading to optimal transportation system performance, with basic assumptions that it follows some given distribution pattern like negative exponential distribution. The problem is eventually formulated into a mathematical program with complementarity constraints and efficient solution algorithm is developed. Finally, numerical examples are conducted to test the model formulation validity and efficiency.

Peer-review under responsibility of the Scientific Committee of ISTTT21
Keywords: travel corridor; time-distance toll scheme; urban density; MPCC.

* Corresponding author. Tel.: +65 6790-5281; fax: +65 6790-5281.
E-mail address: wangzhiwei@ntu.edu.sg

Peer-review under responsibility of the Scientific Committee of ISTTT21
doi:10.1016/j.trpro.2015.07.008

1. Introduction

Urban traffic congestion in the morning commute is becoming more and more severe in many large cities. Due to limited land resources and prohibitively huge financial investments, we cannot afford to build up more new transportation infrastructures. The ideal way is to best manage the interactions between urban planning and transportation system. Urban form and urban density distribution are the key issues of urban planning and have significant effects on achieving sustainable transportation system. Many big cities, like Singapore, are expecting rapid population growth in a near future. It is then necessary for the urban planners to understand how to plan and allocate the new population growth in a closed city while making it possible to ensure transport systems with optimal performance. On the other hand, to alleviate peak hour commute traffic congestion, many management and control measures are applied. In cities like Singapore, electronic road pricing (ERP) is in use and it is going to be upgraded to the next generation ERP, enabling time-distance toll scheme based on GPS technology. It is imperative for urban and transportation planners to understand how urban density distribution should be planned to optimize the transportation system performance in a multimodal travel corridor, with the aid of time-distance road pricing scheme.

Many previous research works have examined the relationship between land use and transportation system. The Lowry model was the initial transportation - land use model using market simulation approach, which was developed in 1964 for the Pittsburgh region (Lowry, 1964). After that, a vast body of studies have been done and comprehensive literature reviews are available (Wilson, 1971; Meyer and Miller, 1984; Wilson, 1998; Wong et al., 1998; Wegener, 2004). For urban population density distribution, empirical studies have confirmed that population density declines as distance to the urban center increases (Mills, 1970), and the negative exponential distribution function is the most common used function to depict the population distribution. Marc (1978) proposed a combinatorial programming model of joint optimization of land use and transportation with different exact and heuristic methods for comparison. Based on game theory, a bid-rent network equilibrium model is generated to formulate the relationship between transportation and residential location as an n-player non-cooperative game, and a path-based heuristic algorithm is proposed to solve the bi-level programming (BLP) model (Chang and Mackett, 2006). As an extended work of Briceño et al. (2008), Bravo et al. (2010) put forward an integrated model to describe the combination of land use and transportation system, which could be formulated as a fixed-point problem. Yim et al. (2011) proposed a bi-level reliability-based land use and transportation combination model with origin-destination (OD) demand following a certain distribution. This model was solved by a genetic algorithm (GA) with a simple numerical example as illustration.

On the other side, as a demand management strategy, road pricing has been proven to be efficient in alleviating traffic congestion. Early works on first best toll pricing (FBTP) mainly focused on the application of the economic principle of marginal social cost pricing (MSCP). Pigou (1920) and Knight (1924) proposed the road pricing idea with MSCP application first, and then it was further studied by Beckmann et al. (1956); Walters (1961); Beckmann (1965); Vickrey (1969). Arnott et al. (1990a) studied various toll patterns for a simple network with parallel routes, and compared uniform and step tolls. The uniform toll only diverted auto drivers from one route to another without cutting their number, and step toll resulted in better efficiency by altering the departure times. Arnott et al. (1990b) presented a comprehensive economic analysis of a bottleneck model with road congestion in the morning peak hour to determine the coarse toll with optimal capacities. Johansson (1997) applied MSCP to maximize the social benefit with optimal road charges, and presented the optimal road charges as a function of speed not traffic flow. Yang and Huang (1998) explored the network equilibrium problem with queue and delay based on the economic principle of MSCP and presented some new properties of the marginal cost pricing. Yang et al. (2004) developed a BLP model to formulate the optimal entry-exit based toll design problem, which was transformed to an equivalent single level model and solved by an augmented Lagrangian algorithm. Compared to FBTP, second best toll pricing (SBTP) is more reasonable and applicable in reality, especially for time-varying and distance-based toll schemes. Chen and Bernstein (2004) proposed a bi-level SBTP design model with heterogeneous users, which could be transformed to a single level nonlinear programming (NLP) model based on several assumptions. Friesz et al. (2004) proposed a theory of dynamic congestion pricing as a continuous-time optimal problem, which showed an analysis of the necessary conditions for the optimal congestion pricing. Friesz et al. (2007) proposed a dynamic toll design problem with equilibrium constraints and showed a direct solution method for a small problem. Particularly, they gave detailed analysis of the user equilibrium (UE) with dynamic tolls and characteristics of efficient tolls. Zhang et al.