Physica A 442 (2016) 417–428

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Modeling, analysis, and simulation of the co-development of road networks and vehicle ownership

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HIGHLIGHTS

- A co-development model of road networks and vehicle ownership is developed.
- Sensitivity tests are developed to determine proper values for model parameters.
- Stability analysis indicates that this model is steady.
- The proposed method can effectively simulate and predict the co-development process.

ARTICLE INFO

Article history:
Received 26 March 2015
Received in revised form 13 August 2015
Available online 28 September 2015

Keywords:
Co-development
Road networks
Vehicle ownership
Stability analysis
Chaos

ABSTRACT

A two-dimensional logistic model is proposed to describe the co-development of road networks and vehicle ownership. The endogenous interaction between road networks and vehicle ownership and how natural market forces and policies transformed into their co-development are considered jointly in this model. If the involved parameters satisfy a certain condition, the proposed model can arrive at a steady equilibrium level and the final development scale will be within the maximum capacity of an urban traffic system; otherwise, the co-development process will be unstable and even manifest chaotic behavior. Then sensitivity tests are developed to determine the proper values for a series of parameters in this model. Finally, a case study, using Beijing City as an example, is conducted to explore the applicability of the proposed model to the real condition. Results demonstrate that the proposed model can effectively simulate the co-development of road network and vehicle ownership for Beijing City. Furthermore, we can obtain that their development process will arrive at a stable equilibrium level in the years 2040 and 2045 respectively, and the equilibrium values are within the maximum capacity.

1. Introduction

The interaction between road networks and vehicle ownership is a complicated process, and thus understanding this interaction is the critical factor to militate urban traffic problems (e.g. congestion, accident, and pollution). Although many studies have been conducted, most of these efforts have investigated the development of road networks or that of vehicle ownership separately, without considering how they interact.

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http://dx.doi.org/10.1016/j.physa.2015.09.042

With regard to the road networks, numerous previous studies mainly focused on the empirical research of urban road networks and their topological characteristics. Porta et al. [1] analyzed the topological structure of road networks of six cities with different forms and historical background; the findings showed that these networks belonged to scale-free networks and exhibited some characteristics of small-world networks. In an investigation of the network efficiency and traffic distribution of the urban road networks of the 20 largest cities in Germany [2], researchers for the first time discovered the power-law features between the number of points and the costs, and the nodes and edges betweenness allowing power-law distribution as well. Paolo et al. studied the growth of London's street network [3]. Results indicated that the growth of the network can be analytically described by logistic laws and that the topological properties of the network are governed by robust log-normal distributions characterizing the network's connectivity and small-world properties that are consistent over time. In addition, some scholars attempted to explore the mechanism of urban road network expansion. One approach is to attempt to extract or generate the optimal structure of networks; several of these scholars developed optimization models based on different objectives [4–6]. In contrast to optimization, the concepts of agent-based interaction and self-organization have been introduced to interpret the development of various complex systems [7,8]. Recently, from the perspective of evolution references, researchers in Italy and France analyzed the evolution of the road network in a large area located north of Milan and Paris [9,10], respectively. They found that natural evolution of a road network is governed by two elementary processes: (i) densification, corresponding to an increase in the local density of roads around existing central points and (ii) exploration, whereby new roads trigger the spatial evolution of the urbanization front. In addition, the evolution will be impacted by interventions of central, top-down planning. In recent years, interest has increased in the co-development of land use and road networks. In addition, several studies attempted to seek the relationship between land use and road networks [11–13].

Models to predict changes in the level of vehicle ownership have been under development since the 1930s. They are essential to the transport planning process and are of interest to government, vehicle manufacturers, environmental protection groups, public transport authorities and public transport operators. Many studies have examined the key factors that result in changes in vehicle ownership [14–16]. They demonstrated that vehicle ownership decisions were based on or impacted by income, license holding, employment, purchase costs, travel distance, age, and other factors. Several studies established the fact that vehicle ownership was lower in areas with good quality public transport options [17–19]. Additionally, higher level of vehicle ownership induces several problems, such as congestion, traffic safety, and increased carbon emissions. Therefore, various policy tools, e.g. congestion pricing [20], high occupancy vehicle lanes [21], direct control measures for vehicles [22], and electric vehicles [23,24], were proposed and implemented to reduce vehicle ownership.

Few studies examined the integrated development of a road network and urban vehicle ownership, leaving their endogenous interaction still poorly understood. In reality, their interaction has profound impact on the quality of life of millions and of society as a whole. The rate at which vehicle demand has grown has often outstripped the improvements in road networks and overwhelmed the institutions responsible for transport management in many cities. As a result, these cities are beset with severe transport problems such as traffic congestion, road accidents, and environmental deterioration, which have a negative effect on residents and their activities. Consequently, how to balance the scale of road networks and vehicle ownership, thereby mitigating those traffic problems, is a significant issue worthy of further study.

This lack of understanding is revealed time and again in the long-range planning efforts of metropolitan planning organizations, where road network change is treated exclusively as the result of top-down decision-making. Non-immediate and non-local effects are generally underestimated in planning practices because the complete network effects are incomprehensible with the current tools, which often results in myopic network expansion decisions. Though urban traffic management makes network growth (decline) happen on the surface, network dynamics are indeed driven by some underlying natural market forces (e.g., economic demand, population growth, and resources limitation). Therefore, understanding how natural market forces and policies are translated into road networks expansion and vehicle growth is essential for scientific understanding, planning, and policy-making.

To fill these gaps, this paper endeavors to understand the development process of road networks and vehicle ownership at the theoretical level, and establishes a co-development model. The growth of vehicle ownership and road network expansion, as well as their interactions, will be considered jointly in the co-development model. In addition, this model will discuss how natural market forces and policies are translated into road networks expansion and vehicle growth.

The rest of this paper is organized as follows. In the next section, a co-development model of road networks and vehicle ownership is presented. Section 3 discusses the stability of the proposed model from two perspectives of theoretical analysis and simulation analysis. It is followed by sensitivity tests in Section 4. In Section 5, a case study is conducted to demonstrate the capacity for real implementation of the proposed model. Finally, Section 6 summarizes the conclusions and future research directions.

2. Model development

2.1. Assumption and notation

To facilitate the description of the proposed model, the change of road mileage R is assumed to reflect the development of the road network.

The key notations and parameters utilized hereafter are listed in Table 1.