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Sustainable urban transit network design

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ABSTRACT

Sustainability is a requirement for modern public transportation networks, as these are expected to play a critical role in environment-friendly transportation systems. This paper focuses on developing an efficient model for solving a sustainable oriented variant of the Transit Route Network Design Problem. The model incorporates sustainable design objectives, considers emission-free (electric) vehicles and introduces a direct route design approach with route structure and directness control. An application in a real world case, highlights the performance and benefits of the proposed model.

1. Introduction

Public transportation (PT) systems ensure equitable access to transportation for citizens and at the same time contribute in mitigating the impacts of traffic on the natural and socio-economic environment. A public transportation system should combine cost and service efficiency to improve its competitiveness and market share (Vuchic, 2004). In recent years, efforts towards achieving environmental sustainability have focused on developing energy efficient public transportation networks (UITP, 2013). In this context, the design of a public transportation network should address different, often conflicting, objectives commonly referred to as "total welfare"; these typically include user, operator and external costs minimization (Kepaptsoglou and Karlaftis, 2009). The associated Transit Route Network Design Problem (TRNDP) is a complex optimization problem, which involves a variety of design parameters, such as route structure, frequencies, vehicle types and so on, as well as different assumptions on demand patterns and travel behavior (Newell, 1979; Kepaptsoglou and Karlaftis, 2009; Guihare and Hao, 2009). Indeed, the TRNDP has been a topic of intense research interest for over 40 years (for an extensive review see Kepaptsoglou and Karlaftis, 2009).

Our work extends the state-of-the-art by investigating the design of a sustainable PT network on which vehicles of different propulsion systems operate (conventional and electric). A non-linear mathematical programming model is formulated; objectives include the minimization of user and operator costs and of environmental impacts. The model's decision variables include route structure, frequencies and vehicle types. An iterative procedure coupled with a genetic algorithm is devised for solving the model. The model is applied to a real-size network of the city of Heraklion (Crete), Greece. The remainder of the paper is organized as follows: Section 2 offers a brief literature review on the TRNDP and states the paper's contribution. Sections 3 and 4 present the model and solution approach proposed for a sustainable transit network design.

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Section 5 discusses the model's application for the city of Heraklion and Section 6 concludes with the paper's major findings and suggestions for future work.

2. Background

The TRNDP has attracted considerable attention in the literature for over 4 decades; Kepaptsoglou and Karlaftis (2009) and Guihare and Hao (2009) offer comprehensive reviews of previous work. As such, this section is limited to (i) recent publications on the TRNDP and, (ii) research efforts on the design of environmentally efficient PT systems.

2.1. TRNDP: recent wok

As noted in Kepaptsoglou and Karlaftis (2009), major elements of the TRNDP include the problem's objectives (conceptual level), parameters, and solution approach (methodological level). The objectives and the solution approach are key issues investigated in many recent papers while TRNDP's parameters (decision variables, assumptions, and parameters) are largely case specific and are related to technical details considered during the problem's formulation. Here we review recent publications based on their objectives and solution approach, as these are mostly related to the contributions of this paper.

The objectives of the TRNDP can be summarized as follows (Fielding, 1987; van Oudheusden et al., 1987; Black, 1995; Kepaptsoglou and Karlaftis, 2009): (i) User benefit maximization, (ii) Operator cost minimization, (iii) Total welfare maximization, (iv) Capacity maximization, (v) Energy conservation – protection of the environment, and (vi) Individual parameter optimization. Total welfare maximization is the most common objective used by recent publications and combines factors such as user and operator costs, unsatisfied demand and external costs (Fan et al., 2008; Beltran et al., 2009; Mauttone and Urquhart, 2009a,b; Marín and Jaramillo, 2009; Shimamoto et al., 2010; Han et al., 2011; Estrada et al., 2011; Gallo et al., 2011; Blum and Mathew, 2011; Roca-Riu et al. 2012; Cipriani et al., 2012b). Only user cost minimization is considered in other papers in the form of travel, transfer, and waiting time minimization (Zhao and Zeng, 2008; Fan and Mumford, 2010; Szeto and Wu, 2011; Shafahi and Khani, 2010; Nikolić and Teodorović, 2013), equity (Ferguson et al., 2012), and service provision maximization (Curtin and Biba, 2011).

From a methodological perspective, approaches for solving the TRNDP can be classified into two main categories: Conventional (analytical and mathematical programming), and heuristics (traditional heuristics and metaheuristics). The combinatorial nature of the TRNDP (Israeli and Ceder, 1993), and the difficulty in realistically formulating the problem with mathematical programming approaches, has resulted to gradually replacing conventional methods with heuristics over the last years (Chakroborty, 2003). Conventional, analytical methods, have been recently proposed by Curtin and Biba (2011) and Estrada et al. (2011), while mathematical programming approaches have been recently introduced by Marín and Jaramillo (2009) and Shafahi and Khani (2010).

In terms of heuristic approaches, the literature exhibits a variety of techniques that mostly exploit metaheuristics for tackling the TRNDP. In such cases, metaheuristics guide hybrid processes for determining routes, frequencies and other network parameters to improved solutions (Kepaptsoglou and Karlaftis, 2009). Relevant efforts include Genetic Algorithms (Fan et al., 2008; Beltran et al., 2009; Shafahi and Khani, 2010; Shimamoto et al., 2010; Szeto and Wu, 2011; Han et al., 2011; Cipriani et al., 2012a,b; Ferguson et al., 2012), Simulated Annealing (Zhao and Zeng, 2008; Fan et al. 2008; Fan and Mumford, 2010; Han et al., 2011), Tabu Search (Zhao and Zeng, 2008; Han et al., 2011; Roca-Riu et al., 2012), Ant Colony Optimization (Blum and Mathew, 2011; Yu et al., 2012), and Bee Colony Optimization (Nikolić and Teodorović, 2013).

We note that the most common heuristic strategy followed for solving the TRDNP is the route generation and configuration approach. This includes an initial generation of a pool of feasible routes, followed by optimal route configuration, i.e. selection and improvement of optimal routes along with frequency determination (Kepaptsoglou and Karlaftis, 2009). Most recent examples of this strategy are the approaches of Zhao and Zeng (2008), Mauttone and Urquhart (2009b), Blum and Mathew (2011) and Cipriani et al. (2012a,b). Alternative approaches, including those of Fan and Mumford (2010), Szeto and Wu (2011), Roca-Riu et al. (2012) and Yu et al. (2012), attempt the direct design and improvement of an efficient set of routes.

2.2. Environmental considerations for the TRNDP

Environmental impacts have – with few exceptions – not been included as objectives in the TRNDP. Among studies that have included some form of environmental concerns are the papers by Delle Site and Filippi (1995, 2001) which incorporate fuel consumption minimization in designing a bus network; veh-km are used as a proxy for consumption. Beltran et al. (2009) consider a heterogeneous fleet of conventional and ecological buses with restrictions in the conventional vehicle network configuration, while Gallo et al. (2011) offer a TRNDP approach in which external costs minimization (private vehicle traffic) is a design objective. Fusco et al. (2013) evaluate the effects of using a combined natural gas and electric vehicle fleet on the network's operating costs. Finally, Jovanović et al. (2014) propose a neuro-fuzzy approach for determining routes and allocating green buses, considering harmful exhausts and noise as environmental externalities.