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Bicycle network design: model and solution algorithm

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Abstract

We propose an optimization framework for urban bicycle network design. The model takes into account interests of the users (who travel along shortest paths) and the planners (available budget). An underlying network composed by street segments suitable to build cycling infrastructure is taken as input. Each network link has construction and user cost, both proportional to the distance. A network link without cycling infrastructure which is part of a path followed by users, has a larger user cost. A multi-commodity network flow mixed-integer mathematical program is proposed and applied to small-sized problem instances to validate the model. The formulation considers the discontinuities of the bicycle network, i.e. the users' paths which include segments without cycling infrastructure. Sensitivity analysis are performed with respect to budget levels and to penalization of user's cost in links without cycling infrastructure. A metaheuristic is proposed to handle large-sized instances. As an additional feature (difficult to formulate in the exact model), the metaheuristic also minimizes the total number of discontinuities by including them into the objective function. The accuracy of the metaheuristic is estimated by comparing with exact results when possible. The methodology is tested using data from the city of Montevideo, Uruguay, including a large-sized underlying street network and origin-destination trips estimated from a household survey. Computational results are obtained with and without minimization of discontinuities, and they are compared with the current bicycle network of the city.

Keywords: cycling; network design; optimization

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1. Introduction

Cycling has been increasingly identified and promoted as a sustainable transport mode which can contribute to mitigate several non-desirable effects caused by other urban transport modes, like traffic congestion, noise and air pollution (Henao et al., 2015). Both practitioners and researchers have turn their attention to methodologies and technologies for planning and operating bike-oriented transport systems, either to attract new users to this mode or to improve the level of service for those who already use it. As some representative examples, we can mention dedicated bike lanes, traffic signals and specific parking spaces (Bendiks and Degros, 2013). A remarkable initiative which has been implemented in many cities worldwide is bike-sharing (Lin and Yang, 2011), which also poses several challenging management issues.

A key aspect of cycling systems (as of any transportation system) with direct influence over their cost and usability, is the infrastructure. In this context, we understand the infrastructure as the space where people can circulate using bikes. Despite specific regulations, bikes are allowed to circulate using the same infrastructure as cars, that is, the city streets. In some cases, other places banned for cars are allowed for bikes, like park trails or pedestrian streets. Though in principle, city streets are sufficient to ensure connectivity between trip origins and destinations of bike users, it has been recognized that specific infrastructure is needed for cycling. Several types of specific infrastructure for cycling have been implemented, each of them entailing different construction cost and attributes perceived by users, particularly safety and comfort (Bíl et al., 2015; Caulfield et al., 2012; McNeil et al., 2015). Often, the infrastructure is built along urban corridors, either main or secondary streets, connecting places of high demand. Decisions regarding where to build cycling infrastructure usually are taken as part of strategic plans, and therefore long-term ones which may include incremental construction along several years. In this context, the planners are faced to the problem of selecting a set of street sections for building cycling infrastructure over them, in such a way that the result is convenient for the users (people who use bike), and subject to a budgetary constraint. Moreover, as it happens with other transport modes, the users perceive the infrastructure (and services which operate over it, when applies) as a network. This means that users plan and perform their trips by connecting individual elements of the infrastructure/service (street sections, bike lanes, bus lines) in order to reach the destination from the origin. Cycling networks can be considered always connected, since by using the street network, all possible destinations are reachable by bike. However, there has been increasing attention paid to the relevance of connected cycling networks, i.e. cycling infrastructure which allows trips entirely within the bike network. Thus, from both local governments and planning agencies (TFL, 2014) as from the academic field (Buehler and Dill, 2016; Krizek and Roland, 2005) the importance of planning cycling infrastructure as a network has been recently highlighted. In this work, we focus on methodologies for optimal planning of cycling networks.

The literature on this topic is relatively scarce. A considerable amount of grey literature (design standards, reports from civil organizations) has been published (e.g. Sustrans, 2014). Krizek and Roland (2005) study the importance of discontinuities on bike networks, however, they do not propose any method for network planning considering this issue. A discontinuity is defined as a point where bike users are forced to leave the cycling network due to lack of such infrastructure, and therefore they have to share the streets with the cars. Mesbah and Thompson (2011) propose a bilevel optimization model where the upper-level aims to simultaneously maximize the share of bike trips and minimize its impact over car travel time due to reduction of street space. The lower-level represents traffic assignment under user-equilibrium hypothesis, for both bikes and cars. The model is solved by a Genetic Algorithm and tested with an example instance comprising 42 nodes, 142 arcs and 30 origin-destination (OD) pairs. Duthie and Unnikrishnan (2014) propose a mathematical programming model which keeps maximum deviation from the shortest path in users' paths and considers cost in the nodes (a relevant component, either for its desirable features as for its high cost). The model is solved by CPLEX and it is applied to several test instances generated from data related to the downtown Austin region. The corresponding network has 75 nodes, 185 arcs and up to 5625 OD pairs. More recently, Buehler and Dill (2016) review different ways of approaching the design of cycling infrastructure, paying attention to the network concept and its components, i.e., nodes and links. In fact, they conclude that much remains to be done concerning methodologies for planning cycling infrastructure considering the network as a whole.

In this work, we focus on models and algorithms for optimal planning of cycling networks, taking into account interests of the planners and the users. The model takes a network of available street sections and a maximum attainable budget level, and delivers a network (connected or not) which minimizes the distance of bike trips given by an origin-