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Optimal traffic calming: A mixed-integer bi-level programming model for locating sidewalks and crosswalks in a multimodal transportation network to maximize pedestrians' safety and network usability

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ABSTRACT

We study the effect that installing sidewalks and crosswalks, as traffic calming facilities, has on the safety and usability of a transportation network with automobile, public transit and walking as modes of transportation. A mathematical programming model is proposed for this problem whose objective is to minimize the safety hazard for pedestrians and the total transportation cost of the network. We utilize a customized greedy heuristic and a simulated annealing algorithm for solving the problem. The computational results indicate that installing sidewalks and crosswalks at proper locations can reduce the overall transportation cost and improve pedestrians' safety.

1. Introduction

In this study, we use traffic calming facilities such as sidewalks and crosswalks (S&C) as pedestrians' infrastructures in designing a multimodal transportation network to enhance pedestrians' safety and increase network usability. We consider walking as a main mode of transportation, besides automobiles and public transit, and pedestrians as one of main users of the transportation system.

1.1. Motivation

In many small communities in the United States, transportation is dominated by a single mode – the motor vehicle. The lack of walkway infrastructures like sidewalks and crosswalks poses a safety hazard to pedestrians since they must walk along busy streets and highways to travel within the city. Since the 1920s, there has been a growing concern about pedestrians' safety because pedestrian fatalities are a major part of all traffic fatalities (Campbell et al., 2004). Pedestrians' safety is defined as the condition of being protected from danger, risk, or injury caused by accidents with motor vehicles. The Federal Highway Administration (FHWA) estimated that 4500 pedestrians are killed annually because of traffic accidents with motor

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vehicles, and as many as 88% of those accidents could have been avoided if walkways separate from travel lanes had been available to pedestrians (FHWA, 2010). This implies the importance of pedestrians' safety in transportation network design for city planners and government. On the other hand, pedestrians are also concerned about safety and consider it as an important factor in transportation (Bahari et al., 2013; Weinstein Agrawal et al., 2008).

City planners use traffic calming measures to improve the conditions for non-motorized street users including pedestrians and to increase drivers' awareness of those users which can enhance pedestrians' safety (Lee et al., 2013; Nadesan-Reddy and Knight, 2013; Prokopich and Wise, 2014). Traffic calming is a combination of mainly physical measures that reduces the negative effects of motor vehicle use, alters user behavior and improves conditions for non-motorized travelers (FHWA and ITE, 1999). S&C are among the most important and effective traffic calming measures for enhancing pedestrians' safety (Campbell et al., 2004). Carefully installed S&C improve the walkability of transportation systems, which not only can enhance pedestrians' safety, but can also encourage more people to walk (Freeman et al., 2013; Friederichs et al., 2013; Gallimore et al., 2011) which results in reducing vehicle miles traveled, alleviating traffic congestion, cutting energy use and carbon emissions, and reducing noise and air pollution (Marshall and Garrick, 2010). However, considering the limited budget for city planners and the large number of possible alternatives for locating and installing S&C, identifying the optimal location for these city infrastructures is an important and challenging issue. Therefore, developing a decision support tool that can help decision makers with identifying optimal locations for S&C in a transportation network is needed.

1.2. Related literature

The transportation network design problem (TNDP) has long been recognized as one of the most difficult and challenging problems in transportation and urban planning. The majority of research in TNDP literature focuses on developing mathematical formulations and solution techniques for improving the utilization of the transportation network through either link improvements (i.e. expanding the capacity) or link additions (e.g. building new streets) (Farahani et al., 2013). The common objective in TNDP is to make an optimal investment decision in order to minimize the total travel cost in the network.

The TNDP is usually formulated as a bilevel, leader–follower problem, Farvaresh and Sepehri (2013), Khooban et al. (2015), Szeto and Jiang (2014) and Yu et al. (2015). The upper level is the designers' problem in which decision makers (e.g. city planners) design the transportation network. The lower level problem is the travelers' problem in which travelers decide on their travel route and mode of transportation. The bilevel structure allows the decision maker to improve the transportation network while accounting for travelers' route and mode decisions (Farahani et al., 2013).

Although there have been many studies of the TNDP, there are still numerous gaps and limitations in the literature such as the following:

(1) Many transportation network design problems address only a single mode, and "the literature of multimodal network design problem is very limited" (Farahani et al., 2013). We found only one study in multimodal TNDP that considers a non-motorized mode (bicycle) (Seo et al., 2005); all other studies focus on either bus and car or on bus, car, and metro (Gallo et al., 2011; Miandoabchi et al., 2012, 2011b; Szeto et al., 2010). In pedestrian transportation literature, most studies are descriptive (Buehler and Pucher, 2012; Millward et al., 2013; Stewart et al., 2016; Weinstein Agrawal et al., 2008), and, to the best of our knowledge, no study has considered walking as a mode of transportation within a network design problem (even though, in everyday life, walking is actually the most important mode of transportation).
(2) Of the few existing studies in multimodal transportation problems, most of them assume no flow interaction between different transportation modes (Beltran et al., 2009; Cantarella et al., 2006; Fan and Machemehl, 2008). However, in reality when the transportation modes share lanes, the flow of different transportation modes do interact.
(3) Most studies in TNDP have ignored combined mode trips where travelers can use multiple modes of transportation during the course of their trips such as park-and-ride, especially in the strategic level decisions (Farahani et al., 2013). An important aspect of multimodal transportation systems with combined mode trips is to provide convenient mode transfer possibilities for travelers. Nowadays, with the advent of technologies like Uber, Lyft, SideCar and Curb, combined mode trips seem more viable than ever before.
(4) The objective in most studies in TNDP is primarily related to travel time (Mesbah et al., 2008; Resat and Turkay, 2015; Yao et al., 2014; Yu et al., 2015), or travel cost such as operator cost, and user cost, e.g. (Cipriani et al., 2006; Fan and Machemehl, 2008; Gallo et al., 2011); one of them addresses safety.

Given these gaps in the existing literature on the TNDP, there is a need for further study that investigates network design from a pedestrian perspective.

1.3. Research scope and contributions

In this paper, we study a TNDP that addresses all of the above mentioned gaps and limitations in the literature toward the goal of extending existing literature to make it applicable to pedestrian transportation. We propose a network design framework for a multimodal TDNP that addresses the aforementioned gaps in the literature: (1) It considers walking as an independent mode of transportation in addition to public transit (i.e. bus) and automobile. This means that pedestrians are