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Minimizing the total costs of urban transit systems can reduce greenhouse gas emissions: The case of San Francisco

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ABSTRACT

Public transit systems with efficient designs and operating plans can reduce both total costs and greenhouse gas (GHG) emissions. Total costs are a sum of user cost and agency cost. In previous work, we explored in various hypothetical city scenarios possible tradeoffs between GHG emissions and total costs for optimally designed transit systems. However, most current transit systems were not designed to minimize total costs. This study aims at finding the potential emission impact when optimizing the total costs of such a system, the MUNI bus network for the city of San Francisco. The continuum approximation (CA) method is used to obtain a stylized representation of the network. Total costs and emissions are derived as functions of system attributes such as headways and spacing. We analyze the optimal total costs and emissions and the corresponding attributes. Our result shows that a significant reduction in GHG emissions is achieved when total costs are reduced simultaneously. The cost-optimal MUNI bus system has a total cost of 0.15 billion $/year and emits 1 680 metric tons of greenhouse gases. These figures amount to about half of the cost and a third of the emissions in the current MUNI bus system. The optimal system has a lower spatial availability but a higher temporal availability of bus service than the current system, which highlights the potential benefits of providing more frequent express bus services.

1. Introduction

Public transportation is often considered an efficient counterpart to private automobiles that has the potential to mitigate emissions. However, current transit systems are not designed to reduce environmental impacts. In the United States, the greenhouse gas (GHG) emissions of typical transit buses per passenger mile are even higher than those of passenger cars, due to the current low average ridership rate (Davis et al., 2009; Chester and Horvath, 2009; FTA, 2010). In recent years, many efforts to mitigate transit emissions have concentrated on developing fuel-efficient replacement vehicles and changing to alternative fuels (Chan et al., 2013; Alam and Hatzopoulou, 2014; Stasko and Gao, 2010; Li et al., 2015; Nocera and Cavallaro, 2016). Another potential approach to reducing transit emissions is through optimizing the design and operations of transit networks (Pternea et al., 2015; Sun et al., 2013; Chen et al., 2017; Gouge et al., 2013).

In the past decade, researchers have proposed various approaches for transit network optimization. Many of them were focused on achieving optimal design to provide a high level of service (LOS) and save users' travel time (Laporte et al., 2000; Zhao and Zeng, 2006; Zhao and Zeng, 2008; Hadas and Ceder, 2010; Shafahi and Khani, 2010; Yao et al., 2014). Some studies have also considered saving transit agency costs to find more economic network solutions (Chien and Schonfeld, 1998; Fan et al., 2009; Daganzo, 2010; Ibarra-Rojas et al., 2014; Jara-Díaz et al., 2014; Sivakumaran et al., 2014). Network characteristics, such as stop spacings and operating frequencies, are optimized to minimize travel time and operating costs. However, the potential environmental impact through network optimization has not been thoroughly studied. Pternea et al. (2015) extended traditional Transit Route Network Design Problem (TRNDP) by incorporating emissions in the optimization objectives. Sun et al. (2013) proposed a bi-level optimization model that computes transit network solutions with low carbon footprints. Both studies used heuristic methods and discrete optimization to approach the optimal solutions, with a fixed weight to monetize emissions against other cost objectives. Though significant emission savings were achieved in their fixed-weight models, it is difficult to get insights when the weight of emissions varies. In the real world, emission objectives are often weighted differently in city-specific scenarios. A complete analysis

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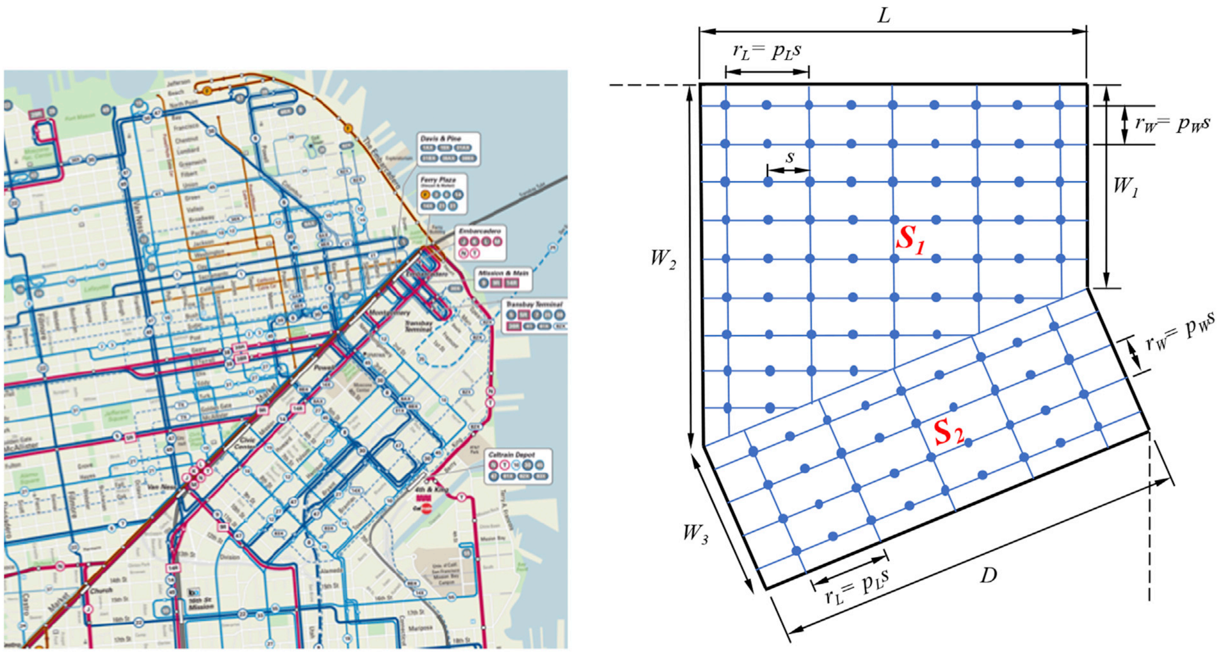

(a) (b)

Fig. 1. (a) The network of downtown San Francisco MUNI system. (b) The stylization of the network in the San Francisco downtown area.

considering a potential range of emission weights could help transit agencies make more informed decisions. Practically, this is not easy to achieve using heuristics and discrete optimization because they are usually highly computationally expensive (Daganzo, 2010).

In our previous work (Griswold et al., 2013, 2014; Cheng et al., 2016), we have introduced a GHG emission constraint in the transit optimization process. The model minimizes costs subject to the emission constraint. Instead of heuristics and discrete optimization, we used continuum approximation (CA) method which is more computationally efficient. By varying the emission constraint, different minimal costs are achieved satisfying the constraint, formulating a Pareto frontier which demonstrates tradeoffs between emissions and costs for optimal transit system design. The frontier is a set of optimal states where it is infeasible to achieve lower costs and lower emissions at the same time. Transit systems operating on the Pareto frontier may not achieve emissions reduction without incurring additional costs, nor achieve costs reduction without incurring additional emissions.

In reality, this conclusion is limited in its practical applications since most current transit systems are not optimally designed. Hence it is likely that they are operating above the Pareto frontier, with both higher costs and emissions. In this case, it is possible to reduce emissions and costs simultaneously by moving a transit system from its current state to a state on the Pareto frontier. Further case studies have also supported this conjecture. Griswold et al. (2017) analyzed an existing bus system in Barcelona, Spain. The work is based on a previously proposed design made by Estrada et al. (2011) that could potentially reduce the costs of the current Barcelona bus system by 17%. In the work of Griswold et al. (2017), they evaluated the proposed design for the Barcelona case and found that it also reduces GHG emissions by 50%.

This paper extends the work to analyze a different transit system, the municipal bus network for the city of San Francisco, California, commonly known as the MUNI bus system. The MUNI bus system is operated by San Francisco Municipal Transportation Agency (SFMTA). It constitutes the major part of the bus services in San Francisco. We build a mathematical model of the MUNI bus network to obtain a relatively accurate representation of the current network. We quantify the societal costs and emissions for the current MUNI system. We identify where the system falls relative to the Pareto frontier, representing the set of optimal designs for the two objectives of societal costs and emissions. The potentials for emissions reductions and the changes in level of service (LOS) are then discussed for the MUNI system.

As in our previous work, the continuum approximation (CA) method is employed to derive the costs and the emissions of the transit system. CA method was initially proposed in Newell (1971) and has been commonly used in various transportation optimization studies (Wirasinghe and Ghoneim, 1981; Kuah and Perl, 1988; Parajuli and Wirasinghe, 2001; Chien et al., 2010; Tirachini et al., 2010; Daganzo, 2010; Ansari et al., 2017). It is also widely used in logistics problems such as facility location, inventory management and vehicle routing (Ansari et al., 2017). Traditionally, transportation and logistics planning are formulated as discrete optimization problems, with discrete distributions of demands, supplies, candidate routes and locations. Although precise, these discrete optimizations are often high-dimensional and NP-hard, which makes them highly computationally expensive especially for large-scale systems. CA methods, though potentially less precise, overcome the computational challenges by using continuous functions to approximate objective and constraint metrics. Network and scheduling details are usually approximated using a set of low-dimensional input parameters and decision variables, such as simple geometric patterns and uniform operating frequencies. The problems become less reliant on intensive computational powers and can be solved by relatively simple analytical operations. The analytical solutions usually have closed-form structures which makes it easier to derive operational insights and identify the cause-and-effect relationship between inputs and design outputs (Daganzo, 2010).

Since CA method requires networks with simple geometric patterns, we choose a stylized network to approximate the real MUNI network. The stylization procedure is described in section 2. Based on the stylized network, we formulate a model to select the optimal bus system attributes in section 3. The optimization results and discussions are presented in section 4. Final conclusions and insights are included in section 5.

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