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Optimal transit service atop ring-radial and grid street networks: a continuum approximation design method and comparisons

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Abstract

Two continuum approximation (CA) optimization models are formulated to design city-wide transit systems at minimum cost. Transit routes are assumed to lie atop a city's street network. Model 1 assumes that the city streets are laid out in ring-radial fashion. Model 2 assumes that the city streets form a grid. Both models can furnish hybrid designs, which exhibit intersecting routes in a city's central (downtown) district and only radial branching routes in the periphery. Model 1 allows the service frequency and the route spacing at a location to vary arbitrarily with the location's distance from the center. Model 2 also allows such variation but in the periphery only.

The paper shows how to solve these CA optimization problems numerically, and how the numerical results can be used to design actual systems. A wide range of scenarios is analyzed in this way. It is found among other things that in all cases and for both models: (i) the optimal headways and spacings in the periphery increase with the distance from the center; and (ii) at the boundary between the central district and the periphery both, the optimal service frequency and line spacing for radial lines decrease abruptly in the outbound direction. On the other hand Model 1 is distinguished from Model 2 in that the former produces in all cases: (i) a much smaller central district, and (ii) a high frequency circular line on the outer edge of the central district.

Parametric tests with all the scenarios further show that Model 1 is consistently more favorable to transit than Model 2. Cost differences between the two designs are typically between 9% and 13%, but can top 21.5%. This is attributed to the manner in which ring-radial networks naturally concentrate passenger's shortest paths, and to the economies of demand concentration that transit exhibits. Thus, it appears that ring-radial street networks are better for transit than grids.

In order to illustrate the robustness of the CA design procedure to irregularities in real street networks, the results for all the test problems were then used to design and evaluate transit systems on networks of the "wrong" type – grid networks were outfilled with transit systems designed with Model 1 and ring-radial networks designed with Model 2. Cost increased on average by a little 2.7%. The magnitude of these deviations suggests that the proposed CA procedures can be used to design transit systems over real street networks when they are not too different from the ideal and that the resulting costs should usually be very close to those predicted.

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1. Introduction

Idealized models have long been used to determine how transit networks should be organized. Holroyd (1967) appears to be the first work to have examined a city-wide system. It explored how a bus grid should be organized in terms of its vehicle headways and station spacings so as to provide optimum service for a given cost. Other works subsequently analyzed other network structures, including those that are purely radial and purely ring-and-radial in form (Byrne, 1975; Black, 1979; Vaughan, 1986).

More recently, Daganzo (2010) examined a hybrid structure that serves a city by means of a square grid of transit routes within a central (e.g. downtown) district, in combination with radial routes that branch throughout the periphery. This hybrid structure generalizes those previously studied. The structure is fully described by just three parameters: the station spacing, which was assumed to be even over the entire city; the vehicle headway in the central district; and the physical size of that district relative to the size of the entire city. The model unveiled how distinct transit modes (bus, BRT and rail) can serve distinct city forms. The hybrid concept was more recently adapted to ring-radial transit networks in Badia, et al. (2014).

All but one of the models cited above (Vaughan, 1986) can be improved by allowing headways and line spacings to vary with location, so that they can be better adapted to a city's travel demand. A nice way of doing this is with continuum approximations (CAs) of the type first proposed in Newell (1971, 1973). In the context of transit, the CA method models station and route spacings as continuous functions of location. Similarly, headways are treated as a continuous function of location and time. Example applications include: Newell (1971), which modeled a single transit station with time-dependent demand; Wirasinghe and Ghoneim (1981), which modeled a corridor; Clarens and Hurdle (1975), which modeled a many-to-one system; and Vaughan (1986).

The above examples illustrate how the design problem can be greatly simplified by modeling a system's numerous decision variables with just a few decision functions. By virtue of these simplifications, the CA models take-on idealized qualities. Yet, their outputs can serve as guidelines for designing actual transit systems in real-world settings. The design objective is a system that fits a city's street layout and achieves costs close to those predicted by adhering to the guidelines as closely as possible. Some design examples with cost comparisons for many-to-one problems can be found in Clarens and Hurdle (1975) and Ouyang and Daganzo (2006).

Despite their favorable attributes, Vaughan (1986) appears to be the only previous attempt to use CA methods to design a many-to-many system with spatially varying headways and line spacings. That model minimizes passenger trip time subject to a fleet size constraint. It looks for an optimum ring-radial transit system atop a dense ring-radial street network, but the model does not allow for a hybrid structure and lacks realism by allowing for arbitrary headway functions, which require numerous transfers, and then ignoring passenger waiting times while transferring.[1]

Two CA models are developed in the present paper that correct this flaw and generalize both Vaughan (1986) and Daganzo (2010). Like Vaughan (1986), Model 1 assumes a circular city with a dense ring-radial street network. It generalizes this reference by allowing for a hybrid transit structure that features both ring and radial lines in the central district, and radial lines alone in the city's periphery. Like Daganzo (2010), Model 2 assumes a square city with a dense square grid of streets. Model 2 generalizes that reference by allowing headways and line spacings to vary within the periphery.

Section 2 below presents the two model formulations and the numerical procedures to optimize the designs. Sections 3 and 4 apply these procedures to a battery of problems in order to: (i) unveil generic properties of the optimum designs (Sec. 3); and (ii) evaluate their costs (Sec. 4).

2. Models

This section presents the models and the analysis methods. Subsections 2.1 and 2.2 introduce the basic assumptions: Sec 2.1 for supply and Sec. 2.2 for demand. Then, Sec. 2.3 formulates the problems and Sec. 2.4 discusses how to solve them.

[1] Non monotonic headway functions require that each radial line be served by multiple transit routes with distinct start and end points. As a result, many patrons must transfer between those routes when traveling radially. This phenomenon needs to be properly captured in a model that accounts for transfer times.