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Rail-based public transport and urban spatial structure: The interplay between network design, congestion and urban form ☆

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ABSTRACT

We examine the effect of spatial differences in access to a railway network on both urbanization and road congestion in a typical 'transport corridor between cities' setup. Using a spatial urban equilibrium model, we find that if the number of access nodes, i.e. stations, is limited, stations contribute to the degree of urbanization. The total effect on road congestion, however, is small. By contrast, if stations are omnipresent there is little effect on urban spatial structure, but a considerable decrease in congestion. This suggests there is a policy trade-off between congestion and urbanization which crucially depends on the type of railway network. We find similar results for a within-city metro network. The key methodological contribution is that, besides the dependence between mode choice and where to work/live, the model allows for differences in the degree of substitutability – local competition – between transport modes. We find that an increase in the substitutability between car travel and railway travel substantially decreases the congestion reduction benefits of a dense railway network.

1. Introduction

Roads have had a considerable impact on urban spatial structure. Baum-Snow (2007a), for instance, finds that without the interstate highway system there would have been more clustering of population (city growth) in the United States. In other words, highways caused suburbanization. This result is particularly interesting given the concerns about urban sprawl and, more recently, the decline of certain urban areas (Glaeser, 1998). In many countries, such as the European countries, but also relatively poor countries, railway travel is an important alternative mode of transport. The yearly passenger-km of rail transport in the EU, for instance, is about 398 billion. Only in India and China the amount of travel by railroads is higher,

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978 billion km and 815 billion km, respectively. By contrast, it is only 9.5 billion km in the US (UIC, 2011). This raises a question about the role of railway travel in determining urban economic outcomes.

To understand the added impact of railway travel on the urban economy it is important to highlight two aspects of such travel that differ from travel via roads. First, supply of railway services is discrete by nature. That is, access to the railway network goes through a train station while access to the road network is nearly continuous. As such, the spatial allocation of train stations has a direct effect on the distribution of population across space (urbanization). Second, railway travel provides an alternative to travel by car, at least to some degree, and, consequently, interacts with the level of road congestion. This interaction depends, however, on the spatial structure of the railway network and the degree of mode substitutability.

The aim of this paper is to examine the interaction between urbanization and road congestion in relation to spatial differences in access to a public transport (railway) network and to highlight the role of mode substitutability as a key determining factor in explaining urbanization and congestion outcomes. We model travel in a generic transport corridor based on the computable spatial urban equilibrium model of Anas and Kim (1996), Anas and Xu (1999), and Anas and Rhee (2006), in the rest of this paper referred to as the Anas model. We measure urbanization by population density and congestion by the difference between the free-flow vehicle speed and the actual vehicle speed inside the corridor.

There are a variety of land use/transport models currently used in the literature. On the one end of the spectrum there is the mathematically elegant, analytically traceable, general equilibrium model of Lucas and Rossi-Hansberg (2002). They model the urban economy of a circular city. Based on this model it is possible to prove that a spatial equilibrium exists, but at the cost of imposing functional form restrictions and only considering a limited number of choice variables. In addition, changes in the parameters of the model can lead to widely different urban outcomes. On the other end of the spectrum there are the partial equilibrium transport models, such as used by Tirachini, among others, in the literature on urban bus transportation (i.e. Tirachini et al., 2014, 2011, 2010; Tirachini, 2014; Tirachini and Hensher, 2011). Transport in these models is often modeled in much detail, but the location of population and transport demand is typically fixed (i.e. travel occurs toward a predefined central business district, CBD). These models can teach us a lot about transport behavior/systems, but less about the interaction with the rest of the urban economy.[1]

The Anas model lies somewhere in between these two extremes. It is flexible enough to allow for a highly non-linear formulation of consumption, production, and travel behavior (a discrete number of zones/stations). The model, however, needs to be solved numerically. Although travel behavior itself is modeled in less detail, there is interaction with other parts of the urban economy. Due to a (multinomial) logit formulation of the origin–destination (OD) choices, changes in the parameter values result in a smooth change in urban outcomes. In sum, the Anas model is ideally suited for our research purposes.

Travel in the standard Anas model, however, occurs by road only. We extend the model by allowing individuals to travel by train – depending on the availability of a station – or car within the same OD pair. This essentially makes car and train competing modes, which we model by a nested logit formulation of the OD (work/live) choice and mode choice. The effect of network design on urbanization and congestion, and the role of substitutability – local competition – between the two modes, is explicitly discussed.

There is ample empirical evidence that mode choices are correlated. Koppelman and Wen (1998), for example, examine different nested logit models and find some evidence that train and car are within a single nest for the Toronto-Montreal corridor.[2] Moreover, not allowing mode choices to be correlated, basically using a multinomial logit structure, can lead to an incorrect estimate of the impact of rail service improvements on rail ridership (Forinash and Koppelman, 1993; Bhat, 1995).

The multinomial logit approach is, for example, used in the transport model of Tirachini et al. (2014), but also by Anas and Liu (2007), Anas and Hiramatsu (2013), and Tscharaktschiew and Hirte (2012). The latter three studies add a second layer of multinomial logit probabilities to also model the commuting, origin–destination, choice. The commuting and transport mode choices are only linked through endogenous travel times/costs. The nested logit we add to the Anas model essentially implies that individuals jointly choose where to work/live and which mode to use based on a broader set of economic variables (i.e. goods consumption, leisure/work, housing/land consumption, which depends on full economic income, travel times, etc.). Moreover, within each OD pair the mode choices are allowed to be correlated. This seems to be more in line with the actual choice problem faced by individuals and it allows us to examine the interaction between urbanization and congestion in relation to mode access and mode competition simultaneously. To summarize, although the benefits and empirical relevance of the nested logit model is evident, it has not, as of yet, found its way into the more formal models of transport and urban land use.[3]

The results in this paper show there is a trade-off between congestion and urbanization which crucially depends on the structure of the railway network and the degree of mode substitutability. First, we find that when the number of access

[1] Transport models are, in some instances, also linked to a wider collection of partial equilibrium models describing other parts of the urban economy (e.g. labor market, housing market). There are many of such combined urban models (for an overview, see Wegener, 2004). Typically, these models can, for example, predict land use for every 100 m grid cell within a particular country/region and, as such, are a very popular tool for policy analysis. These models are, however, typically based on a large number of reduced form equations (the underlying economic choices are no longer directly modeled). In these models, it is virtually impossible to identify the underlying mechanisms that lead to a particular outcome, something we are particularly interested in.

[2] For a discussion of the different nested logit (transport choice) models, see Wen and Koppelman (2001). For a broader discussion of transport modeling and logit models, see Ortúzar and Willumsen (2001).

[3] One particular reason is that it is a highly non-linear approach, which makes it difficult to get clean analytical results. Specifically, it requires the simultaneous modeling/interaction of congestion, urbanization, and railway travel (discrete access), substantially increasing the dimensionality and non-linearity of the model.