Introduction

Evidence from all around the world shows the existence of strong linkages between urban transport networks and urban structure (Newman and Kenworthy 1996 [1]). The classical urban economics theory developed by Alonso [2], Muth [3] and Mills [4] offers solid background to investigate the influence of transport networks in urban context. The standard monocentric city model (Brueckner 1987 [5]), although limited (see Anas, Arnott and Small 1998 [6] for an overview of criticism against this approach), is a simple, stylized framework to understand the linkages between land use, rent levels and transport characteristics (see for example Fujita [7]). In the stylized city represented by the model, urban residents are commuting to a central business district (CBD) that concentrates all the jobs and is reduced to a zero length point. The choice of transport system characteristics is crucial to determine the commuting costs in the city.


However, all of these papers make the assumption of availability of both transport modes at every location within the city. While in real cities dense road network is generally accessible from anywhere, this is not the case of mass transit lines, especially when distance to the CBD increases. Anas and Moses (1977) [13] thus show that competing dense and sparse radial networks can result in different urban forms according to transport characteristics. Baum-Snow (2007) [14] studies the influence of adding faster radial highways on central population density but in this paper all the residents use the same mode (with fixed costs assumed to be zero) with only variable costs varying according to the location.
Despite the abundant literature, it is still not clear under which circumstances the opening of public transit lines in a city leads to urban sprawl or to higher population densities in the CBD. This paper aims at investigating the effects of public transport networks on city shapes according to their characteristics. As a first approach, a standard monocentric city model with multiple transport modes is used to describe the economic forces that influence rents levels and thus residential choices. In a second time, the NEDUM-2D (Viguié and Hallegatte 2012 [15], Viguié and al. 2014 [16]) model inspired by the Alonso [2], Muth [3] and Mills [4] theory is calibrated on the Paris urban area to analyze the effects on city structure of the dense central metro, tramway and bus network operated by RATP and the sparse suburban express mass transit and bus system operated by SNCF.

A linear model to explain the mechanisms

We begin by considering a simple linear city model. While not being very realistic, this version gives us a simple overview of household residential choices to draw first conclusions about the impact of public transport infrastructures on the city. We suppose that the city initially spreads along an infinite uncongestible transport axis with a zero length CBD located at the coordinate \( r = 0 \) point. \( N \) households with homogenous income \( Y \) chose to live along the axis on either side of the CBD and commute twice a day to it. The daily generalized commuting cost for a resident living at a point of coordinate \( r \in [-\infty, +\infty] \) and using mode \( i \) is \( C_i(r) \). We further suppose that households pick the cheapest transport mode at each location to commute. Generalized transport cost \( C(r) \) at point \( r \) therefore reads \( C(r) = \min_i(C_i(r)) \). The strictly quasi-concave well-behaved utility function of each household is denoted \( U(x, q) \), where \( x \) is the amount of consumption of a composite good with unity price and \( q \) is the residential lot size. The residential choice is therefore expressed:

\[
\max_{x,q} U(x, q) \text{ subject to } x + R(r)q = y - C(r) \tag{1}
\]

where \( R(r) \) is the rent per unit of land at \( r \).

At equilibrium, each household achieves a constant utility level denoted \( \bar{u} \) no matter his or her residence (otherwise free mobility would cause households to move to higher utility locations). A common way to study this problem (see Fujita [7]) is to introduce the bid rent function:

\[
\Psi(r, \bar{u}) = \max_{x,q} \left\{ \frac{y-C(r)-x}{q} \middle| U(x, q) = \bar{u} \right\} \tag{2}
\]

and the bid max lot size function \( q_i(r, \bar{u}) \). The former is the maximum rent per unit of land that the household residing at \( r \) can pay while reaching utility level \( \bar{u} \) and the latter is the optimal lot size. Landlords rent land to the highest bidder at each location, the land rent function is thus given by:
\[ R(r) = \max(\Psi(r, \bar{u}), R_A) \]  

with \( R_A \) the agricultural rent. The city extends from \( r_L \) to \( r_R \) and two conditions are required to meet equilibrium:

\[ \Psi(r_L, \bar{u}) = \Psi(r_R, \bar{u}) = R_A \]  

\[ \int_{r_c}^{r_L} \frac{1}{q(r, \bar{u})} \, dr = N \]  

Equation (4) means that at the urban fringe the bid rent must equal agricultural rent while equation (5) simply depicts the fact that all the city population must be accommodated within the city.

We introduce three transport modes to reproduce the structure of Paris transport network with simple linear generalized costs. Figure 1a below shows the generalized costs in the city in the reference case with the blue line representing RATP users located close to the slow but dense metro network available on both sides of the CBD, the green line representing SNCF users living within the vicinity of the fast suburban train network located only to the right of the CBD, and the red line representing car users who benefit from dense anisotropic fast network but have to pay higher fixed cost. The resulting rent profile also appears in Figure 1. We show that removing the RATP or SNCF network has very different consequences on the rent profiles and urban sprawl (see figure 1b and 1c).

*Figure 1. Generalized transport costs and rent profiles in the linear model calibrated on Paris*

![Generalized transport costs and rent profiles in the linear model calibrated on Paris](image)

This first approach allows us to explain how a dense and slow public transport network like RATP metro system leads to more compact cities whereas fast sparse suburban SNCF trains lead to urban sprawl.
Application with NEDUM-2D

NEDUM-2D (Viguié and Hallegatte 2012 [15], Viguié and al. 2014 [16]) is a land-use transport interaction model which relies on the classical urban economics’ framework. It aims at explaining the spatial distribution – across the city – of the costs of land and of real estate, housing surfaces, population densities and building heights and densities.

The equations of the model are slightly more complex than in the theoretical linear case. One major difference is that housing construction is endogenous and driven by changes in rents. Another difference is that different transport modes can be used by residents at each location within the city (a discrete choice model is used to compute modal shares).

We use this model calibrated on the Paris urban area, with a grid of 10000km² with cells of 1km². The model accounts for land-use constraints on the Paris agglomeration. Transportation costs include monetary costs such as the cost of gasoline and the cost of time, with comfort taken into account. We assess them using the spatial structure of the Paris transportation networks (roads and public transport) and real time schedules from operators RATP and SNCF open data.

Population density is computed using this model in the Paris area (figure 2a). This reference case is used to calibrate the model to best represent the characteristics of the city. Like previously, we compare this reference to simulations with no RATP (figure 2b) or SNCF network (figure 2c). It appears that while the dense public transport system operated by RATP tends to make the city more densely populated around the CBD, the suburban lines operated by SNCF tend to attract people further away from the city center, sprawling the city around public transport suburban stations remote from the CBD. We also investigate the rent profiles, housing surfaces and built-up area.

We further conduct a backward analysis on Paris urbanization from the early 1900s to 2010 and manage to explain most of the city shape’s evolution in relation to the transport system changes.

Through the example of Paris, this paper provides helpful insights into the economics lying underneath city structure evolutions and urban sprawl. It shows that public transport systems can either help fight against urban sprawl or on the contrary dramatically reinforce people’s delocalization away from city centers depending on the networks’ characteristics.
Households per km²

Figure 2(a). Households density in the reference case

Figure 2(b). Households density without RATP operated lines

Figure 3(b). Households density without SNCF operated lines
References


