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Assessing Spanish mobility through Complex Networks

Massimiliano Zanin[1,†], Sophie Ladousse[1] and Ricardo Herranz[1]

[1] *INNAXIS Foundation & Research Institute, Madrid, Spain*

Abstract. In this contribution we present a model of the Spanish mobility infrastructures based on Complex Networks. A Scheduled Network object [Chaos **19**, 023111 (2009)] is used to calculate the cost, in terms of time duration of the trip, for passengers going from any point of the Spanish geography, to the airport of Madrid Barajas. Users are distributed between different transportation modes (normal and high speed train, car or flights) according to a *logit* economical model of utilities, which includes duration of the trip, prices and delays in modal changes. As a result, some important metrics of the transportation system are assessed, like citizens' mobility or environmental impacts of mobility.

Keywords: Complex networks, Scheduled networks, air transport system, high-speed train, mobility, environmental impact
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1. Introduction

In the last decade, many natural and virtual systems have been analyzed through Complex Networks, as this mathematical theory allows a relatively simple study of very complex topologies. Transportation systems are not an exception: air, subways networks or streets inside the cities [1] are some examples. This contribution tackles the problem of the high interconnectivity of different transportation modes, and how passengers can take advantage of this characteristic: in other words, we assess the effects of intermodality for a passenger going from any point of the Spanish geography, to the airport of Madrid Barajas.

2. Modeling the Transportation Network

The model we propose is based on two layers: the first to manage the scheduling information of the different transportation modes, while the second simulates the preferences of users. Lastly, a third layer is added to estimate the environmental impact of transportation.

2.. 1 Transport scheduling

Although Complex Networks have been extensively used to study different kinds of transportation networks, like the Air Transportation System or streets in a city, usually time information has been deleted. Intuitively, time is an essential ingredient of any movement: an aeronautical network can be well connected, that is, can have many flights between cities, but at the same time may offer a low mobility due to a bad synchronization between take-off and landing times.

To include time information, i.e., the scheduling of a transport mode, one of the authors recently proposed a modification of Complex Networks formalism, called Scheduled Networks [2]. Within this framework, *standard* nodes (that is, the main destinations inside the network, such as cities, subway stations, and so on) are represented by a group of *primary* nodes; to these, some *secondary* nodes are added to account for the time needed to go from one primary node to another one.

One of the advantage of Scheduled Networks is that links can be dynamically activated or deactivated according to the scheduling information. This is not the same as weighting the links according to the distance (or the duration of the trip), as done in previous works (see Ref. [3]); two cities can be near, or be connected by fast airplanes, and at the same time have only a few flights each day: the real time that each passenger must spend in the trip may therefore be underestimated. More information about this framework, how to construct such kind of networks, and how to adapt classical network metrics to scheduled scenarios can be found in Ref. [2].

In order to account for time information of the Spanish transportation network, a Scheduled Network has been created with information about trains (both normal and high speed) and flights. This information has been obtained in the web-pages of *Renfe* (the Spanish trains administrator) and *Iberia*, respectively. Road movements (i.e, by car) have been included separately, as they have no scheduling limitations. Each trip between two points of the Spanish territory has been divided in a first urban segment, with an average speed of $30km/h$, and a second interurban segment ($90km/h$).

2.. 2 Economic and environmental models

Once the travels' durations have been obtained, from any point of the Spanish geography to the airport of Madrid Barajas, it is necessary to integrate this information within an economic model to understand how many passengers will distribute between the different transportation modes. Following the literature, we have used a *logit* model [5], where the *utility*, that is, the relative *usefulness* of a transportation mode with regards to the others, is calculated as:

$$U_m = k_m + \alpha C_m + \beta T_m + \beta' W_m \tag{1}$$

In this equation, U_m is the utility of the transportation mode m, where m accounts for normal and high speed trains, air transportation, and car. α, β and β' are elasticities to trip cost (C_m), duration and waiting time (T_m and W_m), respectively (values used were taken from Ref. [4]).

As a third layer of the model, we introduce an estimation of the direct environmental impact of those transportation modes, by calculating the quantity of CO_2 produced by each passenger. Other negative impacts, such as noise, soil utilization, NOx, or indirect CO2 emisions (due to infrastructures' construction), whose estimation is still a field of debate, have been neglected. These estimations have been developed by integrating different sources of information: for trains, power consumptions published by *Renfe*, and the Spanish production mix (source: *REE monthly bulletin, July 2009*); for aircrafts, Ref. [6]; finally, for road vehicles, we use the information in Ref. [7].

3. Utilities, Time and Environmental impacts

In this section, we present some results obtained with this model of the Spanish mobility. In Fig. 1 are represented the maps for (top to bottom) utility, emitted CO_2 and travel times, at different hours of the day: from left to right, at 1 AM, 7 AM, 1 PM, and 7 PM. Each point represents the evolution of the considered factor (weighted mean utility, mean CO2 emissions or mean duration of the trip) for a passenger traveling from that point, up to Madrid Barajas; the actual place where the CO_2 has an environmental impact may vary: for instance, the electricity which moves trains is produced all over the Spanish geography, and aircrafts emissions can be transported by the large scale atmospheric circulation.

Results are intuitively consistent with what should be expected from a mobility analysis. Utilities (and travel times) have a maximum (minimum) where an important city exists: in those cities, customers will have the possibility to choose between different high speed trains or flights, thus improving their utilities and reducing the connection time.

Of special interest is a region in the north-east, where connectivity is quite low - it can be easily identified by the red triangle in the last picture of Fig. 1; this zone approximately corresponds to the neighborhood of Huesca: here, no high train exists, and no regular flights connect its small airport with Madrid (only a regional airline operates in this airport, but mainly during week-ends).

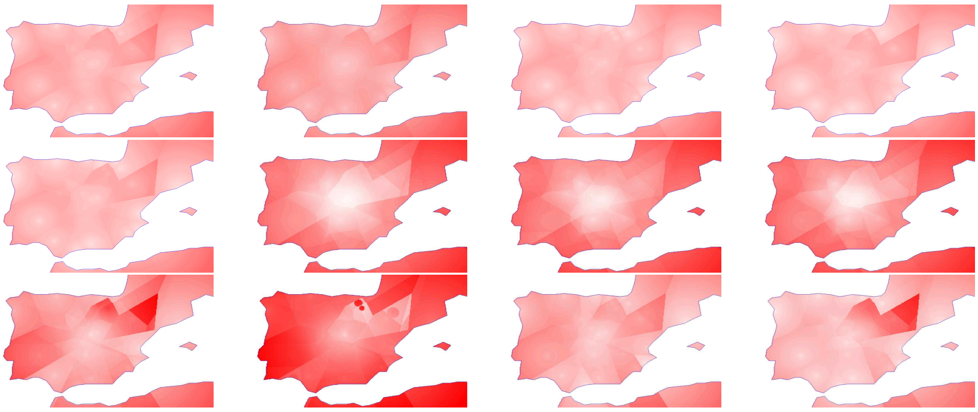

Figure 1: (Upper group) Evolution of the utility in the Spanish geography. Values range from -10 (red) to 0 (white). (Central group) Evolution of the emissions of CO_2 per passenger. Values range from 0 (white) to 100 (red) Kg of CO_2. (Bottom group) Evolution of the time (in minutes) needed to go from each point of the Spanish territory, up to Madrid Barajas. Values range from 0 (white) to 1000 minutes (red).

Clearly trip times are higher here than in other regions, as the user is forced to reach another city by car.

4. Conclusions

This contribution shows how Complex Networks can be used to assess the mobility of a transportation system; this is done using a framework proposed by one of the authors in Ref. [2], which allows to include scheduling information inside the adjacency matrix of a network. A specific example has been analyzed, namely a passenger going from any point of the Spanish geography, to the airport of Madrid Barajas; results highlight regions of low connectivity, especially near the city of Huesca, due to the lack of high-speed trains or air connections.

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