# ENVIRONMENTAL BENEFITS OF INTERMODALITY: THE EXAMPLE OF MADRID BARAJAS

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## ABSTRACT

Environmental impact of transport modes is a growing issue in our societies, especially from the point of view of climate change (mainly $CO_2$ emissions) and air pollution. This topic is gaining more and more attention when planning transport infrastructures, next to more classical considerations like economical and social sustainability. A paradigmatic and up-to-date example is the construction of a high-speed train station in the Spanish airport of Madrid Barajas. The present work studies the environmental impact of the construction of this station in terms of emissions, as well as the effects on population mobility. The model is a simulation of the different possibilities offered to a traveler going to Madrid Barajas from any point of the Spanish territory to catch an international flight; customers' choices are defined through statistical models based on real data, while the dynamics of the transport modes is studied via a Complex Networks approach. The results synthesize the impact of increasing the interconnectivity between air transport and high-speed train networks in this specific context; but they also represent a methodology to assess the impact of any modification in transport networks within a strategic analysis.

KEYWORDS

$CO_2$ emissions, high-speed train, intermodality.

## 1. Introduction

In the last decade, Complex Networks (Boccaletti, 2006) have been a valuable tool to analyze natural and man-made systems. Such networks are an evolution of the mathematic theory of *graphs*: a collection of vertices (also called nodes) and a collection of edges (links) that connect pairs of vertices. In spite of this simple definition, complex networks allow to understand a wide variety of non-trivial structures, along with their evolution in time.
Transportation systems are not an exception: air (Guimerà, 2005; Lacasa, 2009), subways networks (Latora, 2002) or streets inside the cities (Rosvall, 2005; Crucitti, 2006) have been explored under this new focus. Some aspects such as centrality, vulnerability or the dynamics of jams' formation have been tackled, and have been explained in terms of network topological properties.

In spite of this, to our best knowledge no study has been proposed of the interconnections of different transportation modes, and how they could affect the environment. Indeed transportation modes are highly interconnected, and one of them cannot be understood without the other ones: for instance, the utility of a flight depends on how easy it is to get to the departure airport; if jams are blocking the access point of that airport at the peak hour, users may opt for other possibilities, like high-speed train. In this contribution, we propose a model of the Spanish transportation system, which includes flights, high-speed and normal trains, as well as cars, and which allows to analyze the interconnections between them; moreover, direct environmental impacts are estimated, for the present situation, as well as for a future scenario with a new high-speed train station in the airport of Madrid Barajas.

## 2. Construction of the model

The model we propose is based on three layers: the first layer manages the scheduling information of the different transportation modes, while the second one 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, time has usually not been taken into account: a connection between two nodes (that is, two cities) was created if there was a flight (or a train) directly connecting those nodes in a given day. In other words, only static representations of the transportation networks have been considered.
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 (Zanin, 2009). 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, in order to account for the time needed to go from one primary node to another one.
Once the network is constructed, connections between nodes are dynamically activated and deactivated according to the scheduling information of each transportation mode. In this way, the resulting topology evolves with time, and the evolution of some interesting metrics can be extracted: specifically, shortest paths and the times to travel from any point of the Spanish geography to the airport of Madrid Barajas are used in this contribution.

Schedule information for trains and flights has been obtained from the websites of *Renfe* (the Spanish trains administrator) and *Iberia*, respectively. We have chosen to include just one airline, as it simplifies the model and its interpretation, and Iberia represents the vast majority of long-range flights departing from Madrid Barajas.

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 30 km/h, and a second interurban segment (90 km/h).

### 2.2 Passengers’ choice model

Once the duration of the trips from any point of the Spanish geography to the airport of Madrid Barajas have been obtained, it is necessary to create an economic model to understand how passengers will use each transportation mode. The reader may think that passengers will always choose the fastest form to get to Madrid, but this is not always true. People have different perceptions of the *utility* of each transportation mode. For instance, someone may be afraid of aircraft, or may prefer the train because it is allowed to use mobile phones, even if the travel is longer.

In order to take into consideration this variability (or, in other words, this uncertainty in passengers' behavior), a probabilistic model has been created. The first step is to define the concept of *utility*, that is, the relative *usefulness* of a transportation mode with regards to the others:

$$U_m = k_m + \alpha C_m + \beta T_m + \beta' W_m$$

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. $\alpha$, $\beta$ and $\beta'$ are the elasticity to trip cost, duration and waiting time, respectively; in this context, elasticity represents the relative quantity of customers that would change their choice when the corresponding parameter is modified. $C_m$, $T_m$ and $W_m$ represent the price of the trip (in Euro), the trip time (in hours) and the waiting time (also in hours).

The parameter $k_m$ represents the base utility of each transportation mode; in other words, the perception of the usefulness that passengers have about that way of travelling, irrespective of prices and times. Due to the lack of real data, in the present study each *k* is set to zero; although this is not an exact representation of the reality, the error introduced is small compared to the importance of trip times and prices.

Elasticity values used in this model have been extracted from a previous study (Nombela, 2008), where they were calculated from a Spanish national survey (Movilia, 2003): $\alpha = -0.00712$, $\beta = -0.36$ and $\beta' = -0.1044$ (all values are common for each transportation mode). An additional parameter has been also introduced to account for extra explicit costs (like taxis or parking costs), whose value was set to $\alpha' = -0.00712$.

Once the utility has been estimated, the proportion of passengers for each transportation mode is calculated by applying the following equation (which represents a standard *logit* economical model, see (Greene, 2008)):

$$P(m) = \frac{e^{U_m}}{\sum_j e^{U_j}}$$

where $P(m)$ represents the probability of choosing transportation mode *m*, $U_j$ is the utility of mode *j*, and *j* runs for all modes.
With this probability, the overall cost, utility and travel time can be calculated (for each point of the Spanish geography), as the weighted mean; the following equation is the example for the cost:

$$C = \sum_j C_j P(j)$$

2.3 Environmental impact

In the last decade, an important field of research, but also of debate, has been the impact of human activities on climate change; within those activities, the different transportation modes have been widely studied, as they are responsible for an important part of the greenhouse gases emissions.

As a third layer of the model, we introduce an estimation of the direct impact of those transportation modes, by calculating the quantity of $CO_2$ produced by each passenger. Other negative impacts, such as noise, land use, $NO_x$, or indirect $CO_2$ emisions (due to infrastructures' construction), have not been addressed.

- Emissions for each train (both normal and high speed) have been calculated for an occupancy rate of 70%, and with the power consumption (in kWh) published by *Renfe*. Information about the Spanish electricity generation mix (data from July 2009) and emissions are reported in the following Table.

| Source | Proportion in the mix | Emission factor ($tCO_2$ / MWh) |
|---|---|---|
| Hydroelectric | 7% | 0.0 |
| Nuclear | 17% | 0.0 |
| Carbon | 13% | 0.95 |
| Fuel / gas | 1% | 0.7 |
| Cogeneration plants | 36% | 0.37 |
| Wind | 10% | 0.0 |
| Others | 16% | 0.25 |

- Aircraft: the fuel consumption has been estimated at 29 g. per seat and kilometer for short flights (less than 350 km), and at 25 g. for long flights; this fuel is then transformed into $CO_2$ quantities (Knörr, 2008).
- Cars: emissions have been estimated for the Spanish vehicles' fleet at 0.06624 kg $CO_2$ per passenger and kilometer (Perez, 2008).

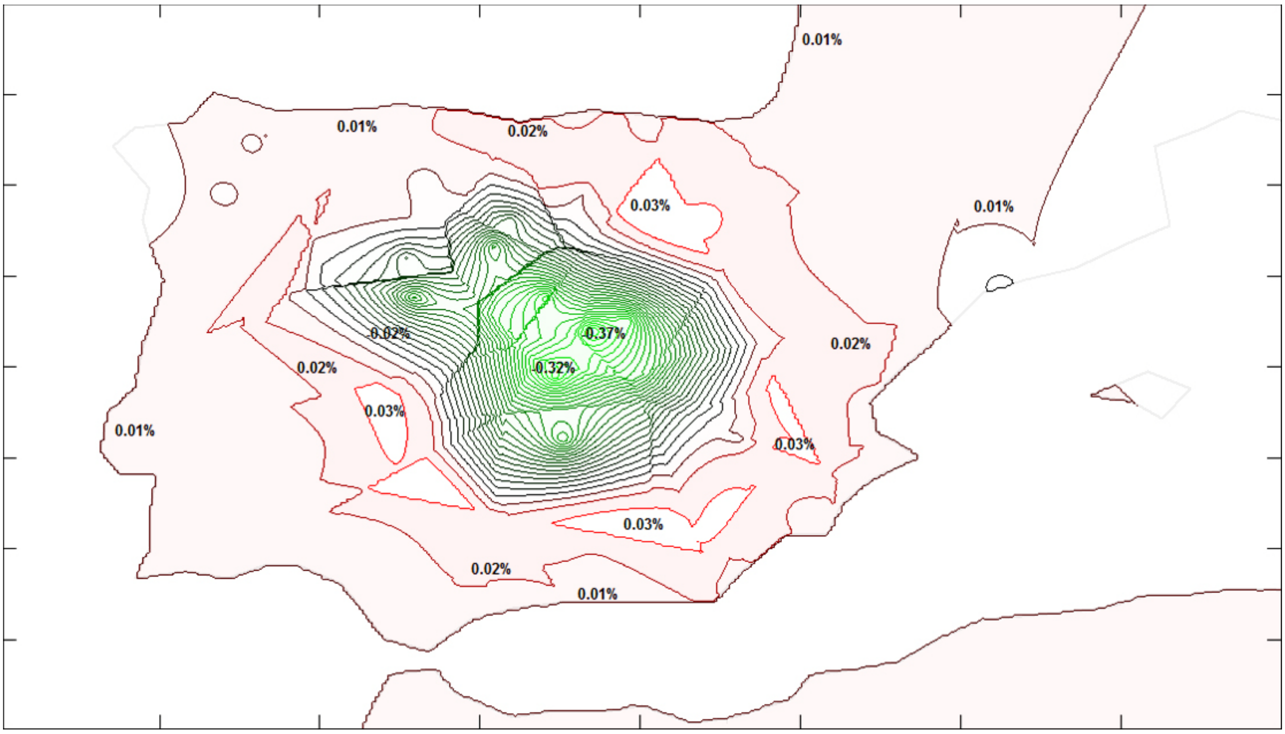
## 3. Environmental impact and intermodality

In this section, we present some results obtained with this model of the Spanish mobility. The next figure represents the maps for emitted $CO_2$ at different hours of the day: from left to right, top to bottom, at 1:00, 4:00, 7:00, 10:00, 13:00, 16:00, 19:00, and 21:00.
Each point represents the evolution of the mean $CO_2$ emissions for a passenger traveling from that point to Madrid Barajas.

The scale of the figure is in kg of $CO_2$ per passenger.

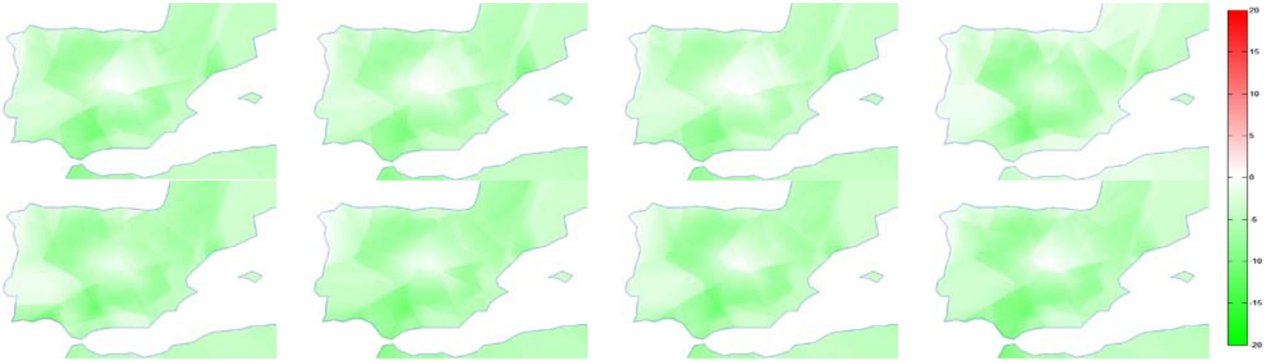
Results are intuitively consistent with what should be expected from a mobility analysis. The environmental impact increases in regions which are far from the destination (Madrid); at the same time, it has some local minima near important cities of the south and of the east of the peninsula: here, customers have the possibility to choose between different transportation modes and especially, where it exists, the high-speed train, which has a low level of emissions compared to aircraft.

The model developed allows also to check the evolution in the quantity of emitted $CO_2$ when some of the initial conditions are modified. In the following figure, the sensitivity of $CO_2$ emission to the price of movements by car is represented; in other words, we suppose that a new tax is introduced, for instance on the gasoline or gasoil, with the aim to reduce the share of this transportation mode.




Results are quite interesting. On one side, in the neighborhood of Madrid, or where a station of high-speed train exists, a reduction is obtained; but, at the same time, in areas which are far away from the center, or that do not have high-speed train, the net quantity of $CO_2$ increases. In those regions, the only alternative transportation mode which is available is the aircraft, which has the highest environmental impact, even higher than car: therefore, users will switch to the air transport, with a negative overall result.

Recently, the construction of a new high-train station in the airport of Madrid Barajas has been announced. This infrastructure will significantly improve the intermodality between this transportation mode, and the air transport; passengers who are traveling to Barajas to link with an international flight will now have the possibility of choosing between both modes, with a smaller penalization due to the modal change.
The effects on the environmental impact are shown in the next figure. As may be expected, the quantity of $CO_2$ emitted per passengers decreases all over the geography, due to the increased utility of high-speed trains.



4. Conclusions

In this contribution, we present a model to estimate the environmental impact (in terms of emissions of $CO_2$) of a passenger going from any point of the Spanish geography, to the airport of Madrid Barajas. Users choose different transportation modes (namely normal and high-speed train, aircraft and car) according to a utility function, which depends on the duration of the trip and its cost. With this model, we have estimated the environmental benefits of two different scenarios, namely an increment of the cost of movements by car, due to a hypothetical environmental tax, and the construction of an intermodal high-speed train station in the airport of Madrid Barajas. From a wider point of view, this model also represents a methodology to assess the impact of any modification in transport networks within a strategic analysis.

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