IJCSS International Journal of Complex Systems in Science

Int. J. Complex Systems in Science
vol. **1(2)** (2011), pp. 96–99

Designing a complex urban bus network

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Abstract. The goal of this research is to develop a methodology to improve Madrid urban bus network. In this context, a set of network parameters is estimated [1]: degree distribution, density, betweenness, and distance between stops (length and diameter average), structures (communities) and robustness. In addition, we relate bus and subway networks characteristics in different districts (areas).

The obtained results allow us to develop a methodology for bus transportation planning (modeling of policies, analysis of the consequences of new urban developments and display of impact indicators) which ensures a good operation and determines the effect of modifications or failures within the network. It is thus possible to analyze scenarios where failures occur in nodes or links in order to propose strategies to keep network performance and prevent degradation of its operation despite the presence of failures. Therefore, the effect of introducing or removing a stop or connection in the network can be determined.

Furthermore, a comparison between subway and urban bus network features allows to improve their current design (issuing of new stops or routes). This work aims to help build an outstanding public transport system in Madrid and its surroundings, thereby reducing private car use and improving the environment in the city.

Keywords: transport networks, planning, complexity

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Received: October 12, 2011
Published: October 24, 2011

1. Introduction

In our work, the subway and urban bus networks in Madrid are abstracted in a graph $G = (E, S)$, where E is the set of nodes corresponding to the stops and S is the set of links between them. A set of structural parameters is analyzed both in the entire network and in each of the district networks to provide a useful mechanism based on complex science to improve these networks and increase the use of public transport in the city and its metropolitan area.

2. Analyzing the subway and urban bus networks in Madrid

Madrid has a complex urban bus network with 204 lines and 4,455 stops and, a subway network with 16 lines and 272 stops. It has 21 districts with quite different population densities and an unequally distribution of stops. A good planning is required.

The subway network is more concentrated than the bus network. The whole bus network has a density $\delta = 0.0010558$, with a maximum distance between vertices of 63. In the subway network, $\delta = 0.0086776$, and the greatest distance between vertices is 38. The average degree in the bus network is $< k >= 4.71156$ while in the subway network is $< k >= 2.3602941$.

The betweenness b_m of a node m in a network is related to the number of times that such node is a member of the set of shortest paths that connect all the pair s of nodes in the network. If g_{nl} is the total number of possible paths from n to l nodes, and g_{nml} is the number of paths from n to l passing through m, then g_{nml}/g_{nl} is the proportion of paths from n to l passing through m. The betweenness for node m is defined as: $b_m = g_{nml}/g_{nl}$.

The districts with highest betweenness stops ($\geq$ 0.07) are similar in subway and bus networks (around 60 %, districts: 1,2,3, 4, 6 and 7). We identify several critical stops where some backup mechanisms could be established.

We also measure the similarities between vertices by means of Walktrap Algorithm which uses random walks on G to identify communities. This method creates a sequence of partitions $(\mu_k)_{1 \leq k \leq n}$, and chooses the best partition of the network, calculating Q_{μ_k} for each partition and selecting the partition that maximizes this parameter. The modularity Q is defined as the fraction of edges within communities minus the expected value of the same quantity for a random network.

The highest modularity in the subway network is 0.722057, with 19 detected communities, while the highest one in the bus network is 0.879664, with 40 identified communities. Figure 1 displays the number of communities by district, so it can be stated that both networks are not estructurated by community.

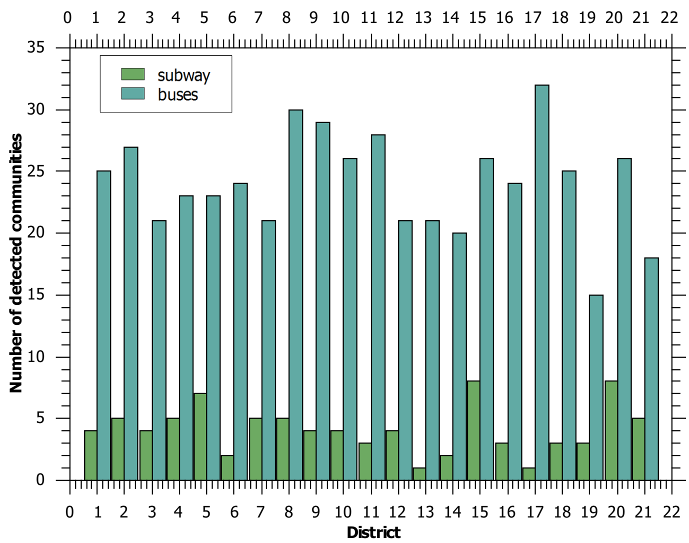

Figure 1: Number of detected communities by district in Madrid

We also analyze the $Singularity(S_{ij})$ of the transport line i in the community j in a district. S_{ij} is defined as $p_{ij}\zeta/\nu^2$, where ζ are the detected communities in the network, ν are the communities where the transport line i appears and $p_{i,j}$ is the probabilty that the line i is present at the community j. In all districts there is a partition on a few lines by communities and some of those lines are more significant than others. In figure 2 S_i is plotted as a function of the community (j) in district 1 for urban bus network. Sij is normalized to its maximum value in a district.

Several studies have estimated the efficiency and vulnerability in networks [2], [3]. We analyze the robustness of transport networks by computing the value of $< l >$ when some stops with high betweenness are removed. We observe in our study that the distribution of distances changes drastically in most of subway networks but not in the bus networks.

We also calculate the sensitivity [3] in $< l >$ as $\varsigma_l = |(< l > /N - < l' > /N')|$ where $< l' >$ and N' correspond to the values of average path length and size of networks with removed nodes. So, $\varsigma = 0,00012167$ in the overall bus network and $\varsigma = 0,01287462$ in the whole subway network, so it can be stated that the latter network is more sensible to failures. This characteristic also appears in the district network.

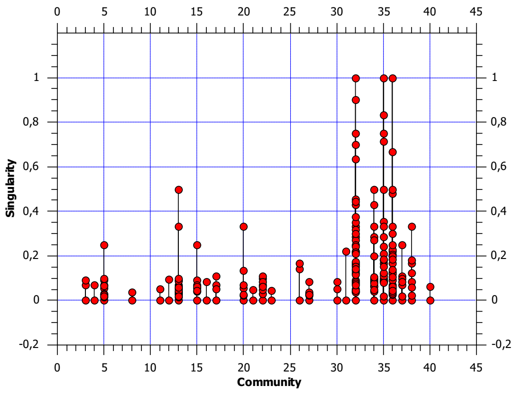

Figure 2: Singularity of urban bus lines in district 1. The singularity S_{ij} of each line i is plotted as a function of community j.

3. Conclusions

The results allow establishing a methodology to improve transport networks topology. It is thus possible to ensure the reliability in the network, analyzing scenarios where failures occur in nodes or links in order to propose strategies to keep their performance and prevent degradation of its operation. Possible synergies (merging stops or paths) can be identified to reduce complexity. It is also possible to find out the effect of introducing a new stop or path into the district networks and then analyze the routes of bus or subway lines to calculate their singularity, determining the necessary modifications.

Acknowledgements

I want to express my appreciation to Emilio Garcia for his assistance.

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