Congestion Phase Transitions in Urban Street Networks

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Cities exhibit different organizational patterns as a consequence of historical, political or economical circumstances, and constitute a paradigmatic example of complex system. In this context, network theory stands out as a fundamental tool facilitating the quantitative modeling of the main urban features and the analysis of the resulting dynamical processes, such as mobility and city growth.

Our work focuses on street networks, which edges represent city roads, while the nodes portray the points where such roads cross. In the literature, the topic has been addressed following different points of views according the purpose and the system characteristics. For instance, the dynamics related to inter-urban roads (also known as arterial roads or high capacity roads), characterized by long segments and limited inter-connection, has been approached employing fluids models, or the fundamental diagram of traffic flow. On the contrary, phenomenology of intra-urban streets is ruled by the underlying network structure and has been traditionally treated by means of graph models

These two types of street networks, which are usually studied independently, are increasingly entangled as cities sprawl over suburban areas. So far, only few works dealt with street networks from an intertwined perspective, and the effects induced by such an interaction have been mostly overlooked. The analysis of the spatial interplay of intra and inter roads networks is the main motivation of the current work.

We focus on monocentric cities and consider the situation in which arterial roads and urban local ones operate on separate geographic spaces. Specifically, local roads are located at the city center, and arterial ones at the urban periphery. Along this line, we introduce a family of random planar network models composed by a dense center surrounded by an arboreal periphery. Such a class of models reproduces previous results in terms of betweenness distribution and, at the same time, offers a considerable advantage in terms of analytical tractability.

In this way, we are able to unveil several unexpected properties of road networks with respect to the congestion phenomena. In particular, it evidences that cities may experience a set of multiple abrupt phase transitions in the spatial localization of congested areas. These transitions define a set of congestion regimes that correspond to the emergence of congestion in the city center, its periphery or in urban arterial roads, and regards the way in which different road classes are entangled to form a unique transportation system. In other word, traffic bottlenecks shift away from the center towards the periphery, as larger areas are incorporates in the urban setting.

The detection of congestion abrupt transition is performed both numerically and analytically and constitutes the main finding of our work. Importantly, this is validated by looking into real road networks. Empirical analysis is carried out over almost a hundred of cities worldwide, and relies on automatic and unsupervised methods. Results show that the multiple abrupt transitions exist in real cities, confirming the prediction performed with our model.

The phase transitions we detect, represents an important resource to improve the efficiency of road networks. The displacement of the traffic bottlenecks towards the peripheral zones, indeed, is crucial to reduce the pressure on the city center, and to avoid the degradation of the transportation system. Therefore, the possibility to control and manipulate such effect constitutes a notable task which has never been performed before [2].

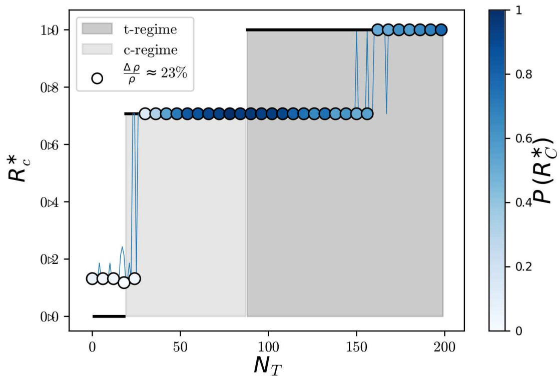

Fig. 1. Congestion radius as a function of the periphery nodes number, showing the various regimes and their transitions. Solid black lines refer to the analytical prediction. Circles represent the experimental results after the introduction of noise, implemented through the addition of random edges to the basic model skeleton till matching a density mentioned in the legend. Each circle is located at the statistical mode obtained with the distribution of R_c after 150 realizations of the model with noise. The color of the circle shows the probability of that value over the experimental R_c distribution. Details about the parameters definitions, and the calculations underlying the figures are discussed in [1].

[1] A. Lampo, J. Borge-Holthoefer, S. Gómez and A. Solé-Ribalta, *Multiple abrupt phase transitions in urban transport congestion*, Phys. Rev. Research 3, 013267 (2021).

[2] A. Lampo, J. Borge-Holthoefer, S. Gómez and A. Solé-Ribalta, *Emergence of spatial transitions in urban congestion dynamics* Journal of Applied Network Science, volume 6 (2021).