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On the efficiency of transportation systems in large cities

L. DA F. COSTA[1,2(a)], B. A. N. TRAVENÇOLO[3], M. P. VIANA[1] and E. STRANO[4]

[1] *Institute of Physics at São Carlos, University of São Paulo - São Carlos, São Paulo, Brazil*
[2] *National Institute of Science and Technology for Complex Systems - Rio de Janeiro, Rio de Janeiro, Brazil*
[3] *Faculty of Computing, Federal University of Uberlândia - Uberlândia, MG, Brazil*
[4] *Urban Design Studies Unit, Department of Architecture, University of Strathclyde - Glasgow, UK, EU*

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Abstract – We report an analysis of the accessibility between different locations in big cities, which is illustrated with respect to London and Paris. The effects of the respective underground systems in facilitating more uniform access to diverse places are also quantified and investigated. It is shown that London and Paris have markedly different patterns of accessibility, as a consequence of the number of bridges and large parks of London, and that in both cases the respective underground systems imply in general, thought in distinct manners, an increase of accessibility.

Underground systems have a critical role in metropolitan areas, affecting urban economic development, people transportation systems, car dependence with related pollution problems, as well as the urban form. Therefore, in the global debate about urban sustainability, underground and other transportation systems there still are big and controversial issues, to the extent that the quantification of their impact represents a major challenge for city planners and local administrations [1–3]. In this letter, we report an analysis of the accessibilities and the effects of the underground systems in the central area of London and Paris street network (area of $13\,\text{km}^2$). In order to do so, we first transform the streets of these cities into complex networks [4–6] so that every crossing or bifurcation of streets becomes a node, while the streets themselves correspond to the links, and then calculate the accessibility of each node. The latter measurement is particularly useful to quantify the potential of each node in accessing in a balanced and homogeneous manner other nodes at specific scales. The mathematical definition of the accessibility of the node i is given as [7–9]

$$A_h(i) = \exp\left(-\sum_{j=1}^{N} P_h(j,i)\log(P_h(j,i))\right) \qquad (1)$$

for $P_h(j,i) \neq 0$, where $P_h(j,i)$ corresponds to the probability that an agent performing a self-avoiding random walk reaches the node j after h steps departing from i. The higher the accessibility for a given h, the more balanced will be the access from node i to the nodes reachable at that distance. Figure 1 illustrates this concept for three subgraphs with different interconnecting patterns. Given the graph in fig. 1(a), we defined the three subgraphs (green, red and blue) by including all nodes that an agent can visit when performing a self-avoiding random walk after departing from a central node (represented by a ticker border line) and with length $h = 2$. Considering R_h as the number of reachable nodes after h steps, it is possible to reach six different nodes ($R_2 = 6$) in all the subgraphs. Note that, although the number of reachable nodes is the same, the transition probabilities are not, indicating rather different patterns of access to the reachable nodes. Figures 1(b)–(d) show the transition probabilities for all the six reachable nodes, for each subgraph. Observe that the probability is inversely proportional to the edge length. The different patterns of access to the reachable nodes affect the accessibility to these nodes. For instance, for the situation shown in (d), the moving agent will most of the times reach the same destination node with transition probability equal to 0.71. This can be properly quantified by the accessibility, which estimates the number of effective reachable nodes, implying that it is larger for the case (b) and smaller for (d).

In addition, as the transport efficiency in cities is related to the number of facilities that one can reach after departing from a given point [10], it is then natural

(a)E-mail: luciano@if.sc.usp.br

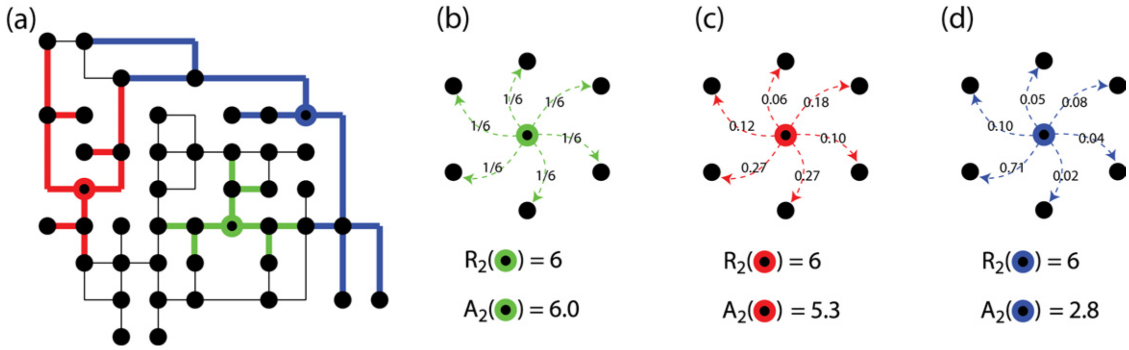

Fig. 1: (Color online) Illustration of node accessibility. (a) Hypothetical network showing three different subgraphs (in green, red and blue). The accessibility A_h considering $h = 2$ and the number of reachable nodes R_h were evaluated for these three subgraphs, departing from the central nodes indicated by the thicker border. (b)–(d) Transition probabilities of the subgraphs considering self-avoiding random walks after $h = 2$. Observe that the transition probabilities are inversely proportional to the edges length. In the three cases the number of reachable nodes is $R_2 = 6$. In (b), the identical transition probability between the reference node and the reachable nodes after $h = 2$ steps implies that the number of accessible nodes becomes equal to the value of the accessibility. In (c) the unbalanced distribution of probabilities led to a lower accessibility. An even less balanced situation is depicted in subgraph (d).

to associate higher values of accessibility with higher transport efficiency. In this paper, we will take the average value of accessibility in order to quantify the efficiency of potential displacements.

The urban network of the central areas of Paris and London were extracted from the OpenStreetMap website[1] using the software Merkaartor[2], which supplies information about both the positions of streets and underground routes. The street networks were coupled to their respective underground networks by linking every underground station to the closest node (considering Euclidean distance) of the street network. The final networks of Paris and London resulted with 11699 (669 from underground) nodes and 6885 (346 from underground) nodes, respectively. The average degrees of these networks are 3.02 for Paris and 2.73 for London.

The displacements of people through the cities were modeled in terms of self-avoiding random walks, so as to avoid going back along the routes. Two different types of walks were considered: respectively to the network with and without the underground system. For the latter, self-avoiding random walks were used. For the former case, *i.e.* including the underground system, several diffusive process starting from each station node were used so that the sum of every diffusion was considered as the weight of the nodes. The agents move over the streets network following the gradient of the nodes weights. In this approach the station nodes can be considered as local attractors of agents and these agents are naturally guided to the closest underground station. When an agent reaches a station it enters in the metro and also navigates through the underground through self-avoid random walks. When it leaves the metro, the weights of the nodes are inverted, so that the station works as a repeller and the agent continues his self-avoid random walk towards the nodes associated to the streets.

The accessibility was estimated for both cities with and without the underground network and a total of 10000 walks were performed for each node, for every city. Each walk had length equal to the average shortest path length of the respective network (*i.e.* 41 steps for London and 37 for Paris steps). The obtained results are depicted in fig. 2, where the accessibility are coded by colors. The values of accessibility obtained for the two cities are organized as histograms in fig. 3. Several interesting insights can be inferred from this figure.

Regarding the historical aspects of both cities, it is well known that in the second half of the eighteenth century, Europe started a season of urban renovation that shaped its major capitals. This process was required in order to accompany the city planners reaction to the industrialism's impact. Paris, London, Berlin, Milan and other major cities underwent radical changes in their urban structure. Different spatial models gave the cities the aspect that they still have [11–14]. Starting form 1864, Paris was totally reshaped by Haussmann and Napoleon III that superimposed a hierarchical grid of boulevards to the old city, through a deeply structural change. One of the challenges was exactly improving the accessibility of facilities and transport by a hierarchical street network [15]. Only fifteen years later, the underground network was superimposed on a well-defined urban street network. On the contrary, London never underwent a unique big structural intervention and its development was achieved through single speculative interventions following the cadastral subdivision of land [14]. This system developed a more fragmented and policentric urban structure and the underground, in this button-up urban growth, played a crucial role in the spreading of the city [15].

[1] http://openstreetmap.org.
[2] http://merkaartor.be.

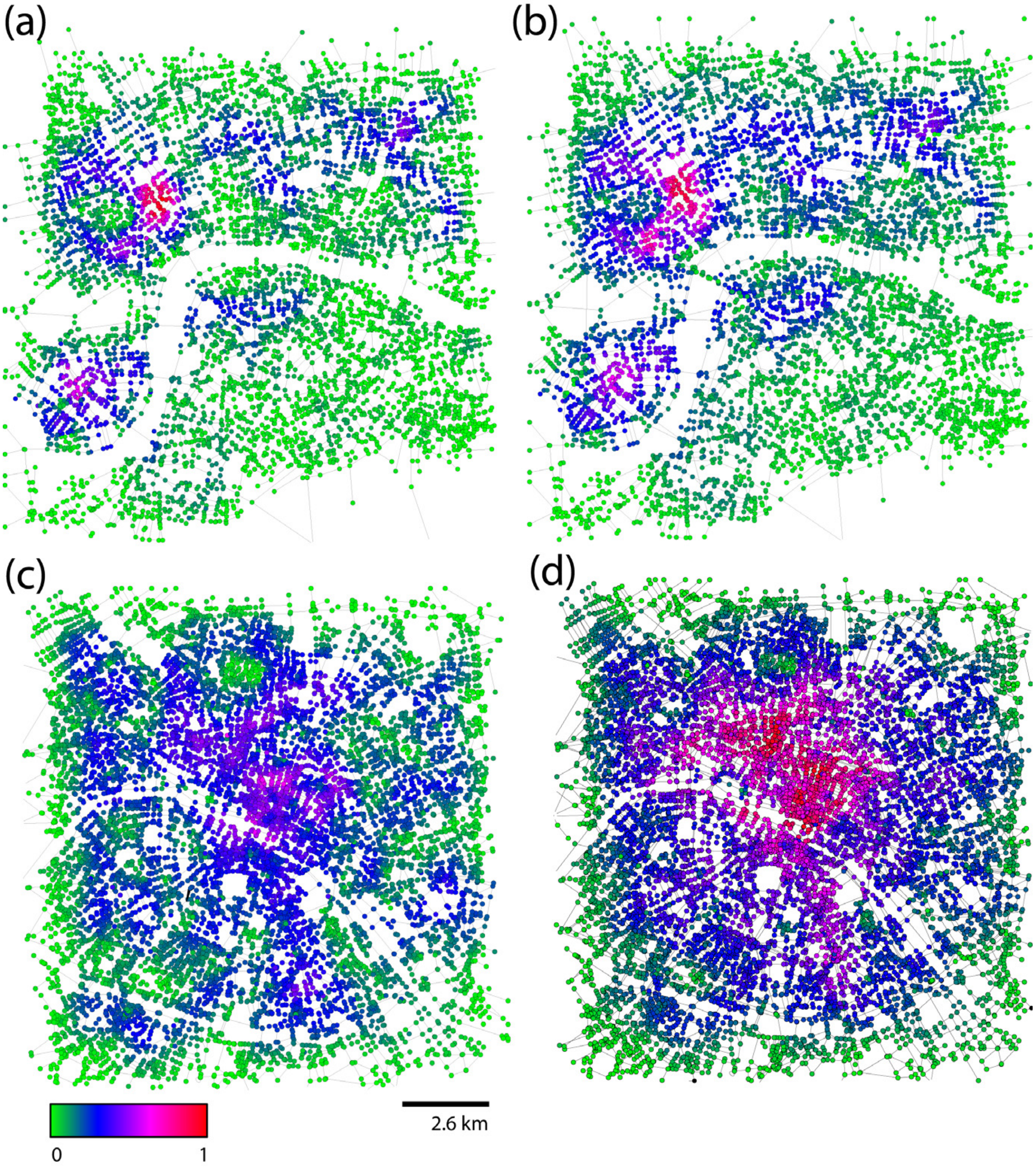

Fig. 2: (Color online) Accessibility obtained for the London transportation system without (a) and with (b) underground. Analogous for Paris without (c) and with (d) underground. Observe that the accessibility values were normalized to the range [0,1]. The minimum and maximum accessibility values were 1 and 69.57 in London and 1 and 217.16 in Paris.

The peculiarities of London as a fragmented city and Paris as a structured one are widely described in the literature [14] and are particularly well captured by the accessibility measurement. Indeed, we found that Paris has a a higher average value of accessibility than London. It is also interesting to note that the fact that the river Thames is much wider than the Seine implied in the southern part of London being less integrated into the remainder network than the counterpart situation in Paris (the Seine has almost 2.5 times more bridges along central Paris than

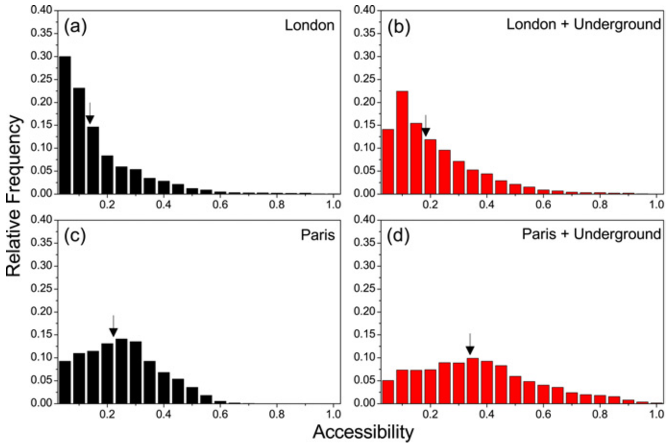

Fig. 3: (Color online) Histograms of accessibility values for London without (a) and with (b) underground. Histograms for Paris without (c) and with (d) the underground system. The arrows indicate the average values.

the Thames within central London). In addition, as it can be clearly appreciated from figs. 2 and 3, the incorporation of the respective underground systems clearly enhanced the accessibility values in both cases. Observe that the efficiency improvement obtained by the introduction of the underground system was almost twice as much larger in Paris (52%) than in London (32%), probably because of the intrinsic higher accessibility of the streets of Paris, since both underground systems have similar topologies.

Our results suggest that the streets layout can heavily affect the total efficiency of urban transportation network. This is also confirmed by the distribution of Betweeness Centrality (BC) [6] and the Search Information (SI) [16]. BC quantifies the importance of each node, counting the number of shortest paths that pass through this node, while the SI measures the information required to walk on the networks along the shortest paths, being more dependent on the density of nodes. We did not observe significant changes in the BC distribution for networks with or without underground probably because BC is not affected by little changes in the network structure and probably because we have not considered underground nodes as local attractor as done for accessibility. On the other hand, the distributions of SI were shifted to left for both cities when the underground systems were incorporated. This result shows that the information required to travel on the networks with underground is lower than their respective versions without underground.

Our results reinforce that the accessibility is a particularly sensitive method for revealing relationships between urban form and transportation systems. Hence there are many applications of the reported methodology, especially in assisting transportation, city planning, and urban form research. Possible future work on this direction includes a deeper qualitative analysis of cities' history and comparisons among a wider range of city typologies.

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