Navigation under congested conditions with limited information

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Abstract

Choosing the best route in congested city is a complicated task given also that condiitions vary both in time and space within days and across days. The uncertainty and the no control on drivers' behaviors contribute significantly to increase congestion and unpredictability of traffic condition. Very often drivers do not know in advance the best path they have to take to reach their destinations with the shortest experienced travel time. In the market, one can find many types of navigator which, based on some traffic estimations from GPS signal and sensors, suggest the shortest time path computed with the current link speeds configuration on the network. But during the trip, the values of link speed can suddenly change and lead the driver to have a higher time delay than if he would take another path alternative.

Taking into account the limits that all traffic models have and the unavoidable unpredictability of accidents and similar non-recurrent events we define a measure that captures the goodness of the alternative path available to drivers traveling in the urban network. We called it the *shortcut length*. Based on simple iterative shortest paths algorithm the authors show an example based on an artificial spatial network and also they illustrate some applications in traffic control, urban design analysis and route recommendation system.

Keywords

shortcut length, urban networks, alternative path, uncertainty, traffic jam, reliability

1 Introduction

Nowadays commuters in a street network of large and dynamical cities have to face not only with the congestion but also with the uncertainty that a congestion can appear somewhere in their planned path. Uncountable different models have been created by the transportation engineers to capture some recurrent traffic patterns and forecast the insurgence of a congestion in our cities. The literature in this domain is vast and the same problem is studied under different points of view: from models inspired by physics (for example in Treiber *et al.* (2000), Helbing and Tilch (1998)), to macroscopic model (Papageorgiou (1990), Daganzo (1995)), from agent-based model (Cetin *et al.* (2003)) to micro-simulations (Barceló *et al.* (2010)), etc.. All these models give a good approximation for estimation of congestion patterns in common days, given the demand, or with online sensors. But it is almost impossible to predict the location, severity and duration of a car accident, or an unpredictable event that creates an unusual congestion in some part of the urban network. In this case, the first thing to do should be to deviate the traffic flow towards a valid alternative path. In this sense, the measure proposed in this paper tries to estimate the property of a path to let drivers the possibility to take a deviation from the shortest path between their origin and destination remaining close, in terms of travel time, to their forecast arrival time.

And so the question to whom this paper tries to answer is: can we estimate which path is more 'sure' to go from a location to another in a specific urban network?

We define as the *surest path*, a path that gives to the driver a possibility to take an alternative street in order to avoid a probable congestion along the pre-estimated path. Moreover, the path between two assigned locations O and D that we will indicate as *surest path*, in order to be the best choice for drivers, it has to have the property that an eventual detour remains close (in a well-defined metric) to the shortest time path between the same two points. We will call *shortcut length* the metric to estimate it. This topic is directly connected with the concept of link criticality and reliability of road networks (Kim and Yeo (2017), Berdica (2002), Chen *et al.* (2007), Du and Nicholson (1997), Jenelius (2009), Jenelius *et al.* (2006), Chen *et al.* (2013)). The approach to reliability analysis proposed in this paper takes inspiration also from some seminal works in complex networks field like in Crucitti *et al.* (2006) where are described some peculiar centrality of spatial networks and in Callaway *et al.* (2000) and Piraveenan *et al.* (2013) where the authors study the effects of percolation in large scale networks.

In section 2 we define an intermediate measure called *shortcut centrality* assigned to each link and fundamental to compute the so-called shortcut length of paths. In the same section are presented 3 different approaches to compute it. Section 3 discuss the main possible applications and implications of the shortcut length. Moreover, an illustrative example with an artificial small network on the effect in route choice of the shortcut length is also given. In the final section are resumed the main results and the discussion about future works.

2 The shortcut centrality

Let $\mathcal{G}(N, E)$ be a spatial graph of N nodes and E links. We will assume that it is connected and directional. We consider also the function $w : E \to \mathfrak{R}$ as the weight for each link. Whenever the function w coincides with the euclidean length of each link we will denote it as $d : E \to \mathfrak{R}$. We will indicate the graph $\mathcal{G}$ with this metric $\mathcal{G}(N, E, w)$ or $\mathcal{G}_w$ where there is no ambiguity.

In the following sections, we propose some different approaches that can be used to study the above-mentioned problem of reliability in an urban path for unexpected urban congestion.

2.1 First approach (basic): cut.

The first approach that we propose is based on the *all_shortest_paths* algorithm, that computes all shortest paths between each couple of nodes. We used Matlab function $distances(A_{\mathcal{G}})$, where $A_{\mathcal{G}}$ is the adjacency matrix associated to the graph $\mathcal{G}(N, E, d) \equiv \mathcal{G}$. That is $A_{\mathcal{G}} = \{a_{ij}\}_{(i,j)\in N\times N}$ where $a_{ij} = 1$ if exist a link $l = (i, j) \in E \subseteq N \times N$ between node i and node j, $a_{ij} = 0$ otherwise. This function returns the full matrix $D \in N \times N$ of the distances, in term of length of the shortest path, between each couple of nodes, that is $D = \{d_{ij} = d^{SP}(i, j)\}_{(i,j)\in N\times N}$. The function *distance* is appropriate for our purpose because it can easily highlight the increment that a change in topology or a drop in efficiency can provoke in the internal network distances between locations.

We proceed in the following way. To simulate an interruption in a street we can *cut* that street, by deleting the corresponding link in the graph, and recompute all the shortest path that used that link. By doing this we can calculate the average increment on the lengths of the shortest path that rely on those couples of Origin-Destination connected in the full network by the cut link. And so, the main idea of the paper is to study for each link its influence in the global efficiency and then do a path-based analysis considering the sum of the values of all links that compose paths.

Consider a link $l \in E$. This first approach considers the graph $\mathcal{G}^{\hat{l}}(N, E \setminus \{l\}, w) \equiv \mathcal{G}^{\hat{l}}$ that is the graph $\mathcal{G}$ without link l. This is made by setting the weight $w(l) = \infty$.

Then we compute again all shortest paths matrix uploading the new (increased) value for those couple of node whose shortest paths passed through link l in graph $\mathcal{G}$. Let $D^{\hat{l}} = distances(A_{\mathcal{G}^{\hat{l}}})$ the new matrix of the lengths of all shortest paths. Now, if we look at the difference between the two matrix $D - D^{\hat{l}}$ the nonzero elements will be the increased values of the relative shortest paths, that is the difference between the previous shortest path and the alternative taken avoiding link l. The average of the nonzero values of the matrix of the difference will be the *shortcut centrality* $S(l)$ of link l. That is, for all $l \in E$:

$$S(l) = \frac{1}{O(D^{\hat{l}} - D)} \sum_{i,j \in N} \left(d^{\hat{l}}(i, j) - d^{SP}(i, j) \right) \tag{1}$$

where $O(d^{\hat{l}} - D)$ is the cardinality of the nonzero elements of matrix $D^{\hat{l}} - D$ that correspond also with the number of shortest paths in $\mathcal{G}$ that use link l.

We repeat this procedure for all links l in E and we obtained the distribution of the *shortcut centralities* of the network.

This first approach simulates the consequences of a link interruption along the shortest paths. On the other hand sometimes it might happen that after having cut a link we lose the connectivity of the graph. We address this issue with two alternative approaches described below.

2.2 Second approach (intermediate): stretch.

In most of the cases a road, because of the congestion, can lose its efficiency and the time needed for a driver to pass through that road becomes longer but not infinite. This fact can be represented in our matricial framework by changing the weight function, increasing the value to those links affected by congestion.

Under this purpose, our second approach is based on a strong incrementation of the weight of links, taken one-by-one. That is for each link $l = (i, j) \in E$ we compute the distance matrix $D^{\hat{l}}_{\alpha w}$ of the graph $\mathcal{G}^{\hat{l}}_{\alpha w}$ that is the graph $\mathcal{G}$ where the weight of link l has been multiplied by a large factor $\alpha >> 1$. Again, from the difference between the two matrices of distances $D^{\alpha w}_{\hat{l}}$ and D we got a similar result than approach 1 without losing the connectivity.

2.3 Third approach (extended): multi-stretches.

If we extended the approach 2 to different links at the same time and we smoothly increase their weights such that we combine the scenario of an extended congestion phenomenon with the computation of the *shortcut centralities* of links.

This third approach tries to simulate a realistic scenario that a driver might experience in a city during a congested period. The main idea, here, is to think about the average incrementation in path length when more links in the urban network decrease their level of service (LoS) and so, the more convenient path in terms of time is an alternative route respect the shortest path. In this sense, we study the effect of contemporaneous ‘stretches’ in the network and the number and quality of the alternative for drivers.

The natural extension of the second approach it will be the following one. Let $C \subseteq E \subseteq N \times N$ be a subset of links E. Let $\bar{\alpha}$ and $\mathbf{t}$ two vectors of dimension the cardinality of set C with $\alpha_k > 1$ and $t_k \in [0, 1]$ for each $k = 1, \ldots, |C|$. We define $D_C^{t\alpha}$ the matrix of distances of the graph where the link weights are $t_{l_k}\alpha_{l_k}w(l_k)$ for all $l_k \in C$ and $w(l)$ otherwise, where, again, $w(l)$ is the length of link l in the graph $\mathcal{G}$.

We can vary $t_k \in [0, 1]$ with $k = 1, \ldots, |C|$ and compute the corresponding $D_{t\alpha}^C$. From the comparison with D, as before, and for each fixed $t \in [0, 1]$ we obtain the average *shortcut centralities* $S^{t,\alpha}(l)$ for each link $l \in E$.

The physical meaning of parameter α and t are the maximum historical delay in link l_k and the current percentage of congestion, that is the fraction of the difference $t\alpha w(l) - w(l)$ to add to physical link length $w(l)$ during the measurement of the shortcut centrality in this third approach. We will refer to it as *partial shortcut centrality* $S^{t,\alpha}(l)$.

Here is useful to make the following remark. If we consider, for each link $l \in E$, the corresponding weight $w(l)$ as the estimated time ($length/speed$) for a drive to travel that corresponding road, this third approach is equivalent to compute the *all_shortest_time_paths* and then the average increment of time due to congestion and/or interruptions.

3 Applications

The main purpose of this paper is to identify the path more *sure* for a driver, assuming limited available traffic information. The limitation can be measured with the fraction of the known link speeds (that is of α_k and t_k for each $k \in C$) over the total number of links E. That means that the recommended path should take into account different factors. Here we consider the following ones:

a) the available on-line traffic data;
b) historical traffic data based on the routine and correlation in demand;
c) accident probability detection;
d) convenient alternative path in case of traffic or interruption.

In particular, our main efforts goes towards a computational result for factor d. In fact, we believe that in order to ameliorate congestion we need, not only an efficient traffic control system but also a good street network analysis. It has to take into account the alternatives that a driver can choose if some unexpected and strong congestion appears along the path from his/her origin to his/her destination.

After having applied one of the above-mentioned approaches to assign to each link its corresponding $S^{t,\alpha}(l)$ we will use it in the following formula to compute the *shortcut length* $W(g)$ of each link g, that is,

$$W(g, t) = w(g) + (\overline{w(g)} - w(g))P_g(t) + \Gamma S^{t,\alpha}(g) \tag{2}$$

where $w(g)$ the physical length of link g, $\overline{w(g)}$ the maximum experienced length. $P_g(t)$ is the probability of having congestion at time t in link g, Γ is a parameter who regulates the weight they we want to give to the (partial) shortcut centrality $S(g)$ of link g. If any congestion probability function $P_g(t)$ is available the formula for the shortcut length that we use is:

$$W(g) = w(g) + \Gamma S^{t,\alpha}(g). \tag{3}$$

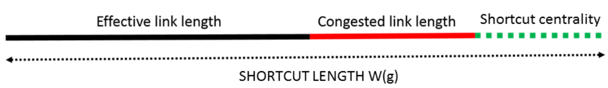
In order to compute $\overline{w(g)}$ we use the following simple method. Let assume that the free flow speed for a link g is v. This means that the average travel time for this link is $\frac{w(g)}{v}$. Let v_c be the average link speed during congestion in link g. The travel time, in this case, will be $t_c = \frac{w(g)}{v_c}$. Let $\rho_g = \frac{v}{v_c}$ denote the ratio between the upper and lower speed limits for g. And so we have $t_c = \frac{w(g)}{v_c} = t_c = \frac{\rho_g w(g)}{v} = \frac{\rho_g \overline{w(g)}}{v}$ With this formula we translate in terms of space the uncertainty and convenience to have a good alternative in case of congestion. And so we consider the probability $P_g(t)$ to have an accident or to have a congestion and use it to compute the expected value of 'effective' length $w(g) + (\overline{w(g)} - w(g))P_g(t)$, that is the corresponding length that a driver would need to travel along the link with free flow speed spending the same amount of time that in the real link but with congestion.

We also define a measure to describe the quality of the path, normalized for the whole network, that we call *convenience path attribute* for each path p that connects an origin O and a destination D.

$$C_p^{O,D} = \frac{d^{SP}(O,D)}{\sum_{g\in p}(W(g))} \tag{4}$$

We notice that $C_p^{O,D} \in]0,1]$ always. In particular, for a path p, the more the $C_p^{O,D}$ is close to 1 the more convenient and sure it will be. It means that in the extreme case, when $C_p^{O,D} = 1$, all links that compose path p from O to D have another alternative link of the same length and the probability of having a congestion is 0 in all of them. While $C_p^{O,D} = 0$ means that at least one link has infinity shortcut length that is the graph is unconnected and location D not reachable from O.

Once we have computed the *shortcut length* $W(g)$ for all $g \in E$ we can run the algorithm of shortest path in the graph $\mathcal{G}(N, E, W)$ to find the surest path that guarantees a path that in case of accident or severe congestion, the drivers can take an alternative route that does not cost in terms of time more than if the same had occurred in any other path from the origin O to destination D.



3.1 Example in toy graph

In this section we present simple example to show the effect of this 'sureness' computation to decide the most sure path, according to our definition.

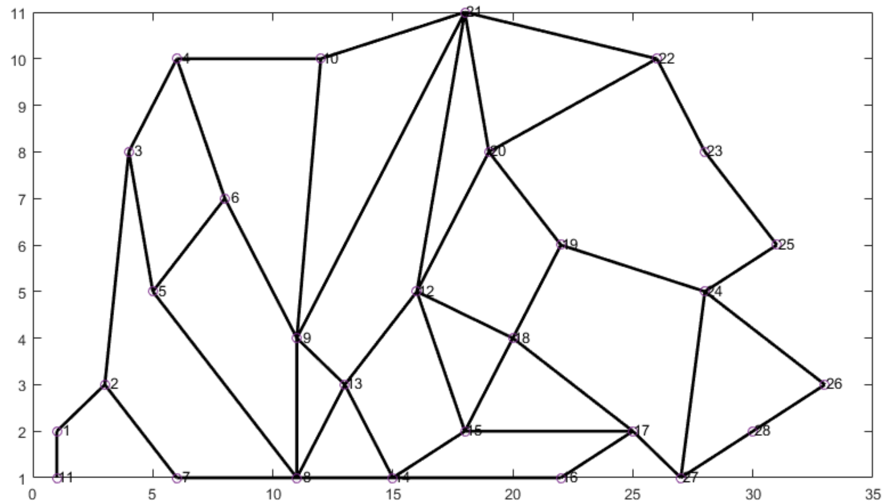


Figure 1: A toy network composed of 28 nodes and 45 links. In our application we consider almost both directional links with some exceptions.

The network that we built and shown in Figure 1 is composed by 28 nodes and 82 links (37 bi-directional and 8 one-way links). We denote $\mathcal{G}^1(N = 28, E = 82, d)$ the corresponding graph. In this road network, we consider only a general free flow condition, that means that the probability of having congestion $P_g(t) = 0$ for each link $g \in E$. This is equivalent to set 0 for the so-called *congestion length* for each link. After having applied approach 2, that is increasing by a big factor $\alpha \approx 10 \max\{length(g)\}_{g \in E}$ one link g at a time and compute the *all_shortest_path* algorithm and the corresponding increment in shortest path length we obtain the vector of the shortcut centrality $S^{\alpha}(g)$ for each link $g \in E$. For the Formula 3 we have the shortcut length $W(g)$ for each $g \in E$ as

$$W(g) = d(g) + \Gamma S^{\alpha}(g)$$

where $d(g)$ is the physical length of the road associated to link g and $\Gamma = 20$.

In the left panel of Figure 2 is shown the shortest path in the directional graph $\mathcal{G}(N = 28, E = 82, W)$ with the new metric W, that is the surest path, from node 1 to node 19. We will name it $p_1 = 1 - 2 - 7 - 8 - 14 - 15 - 18 - 19$. We remark that Figure 2 is made by using Matlab function *view(biograph)* and this means that it is just a useful topological representation and the link length does not correspond with the graphical representation. Nevertheless, it has been marked next to each link the relative shortcut length.

We said that our definition of a sure path is based on the alternative that a path offers to drivers whether an accident or a congestion occurred. In this simplified scenario, we consider that such an event is totally random and so we based our analysis just in alternative length and degree of freedom for a driver along a path. With the aim of showing the effect of remaining stuck on a road without an easy alternative, we eliminate from graph $\mathcal{G}^1$ 3 links. In particular, the links that connect nodes $15 - 12$, $15 - 17$, $14 - 16$. We notice that none of the deleted links belonged to p_1 but they just give to a driver in p_1 the possibility to take an alternative (at Node 14 and 15). With just this little changes we computed again the new shortcut length $W'(g)$ vector relative to graph $\mathcal{G}^2(N = 28, E = 79, d)$. In the panel on the right in Figure 2 is showed the result of the surest path in $\mathcal{G}^2$. We will denote it $p_2 = 1 - 2 - 3 - 4 - 10 - 21 - 20 - 19$. It is completely different from path p_1 and the only cause was the fact to have less possibility to take a deviation in order to eventually avoid congestion along path p_1 in graph $\mathcal{G}^2$.

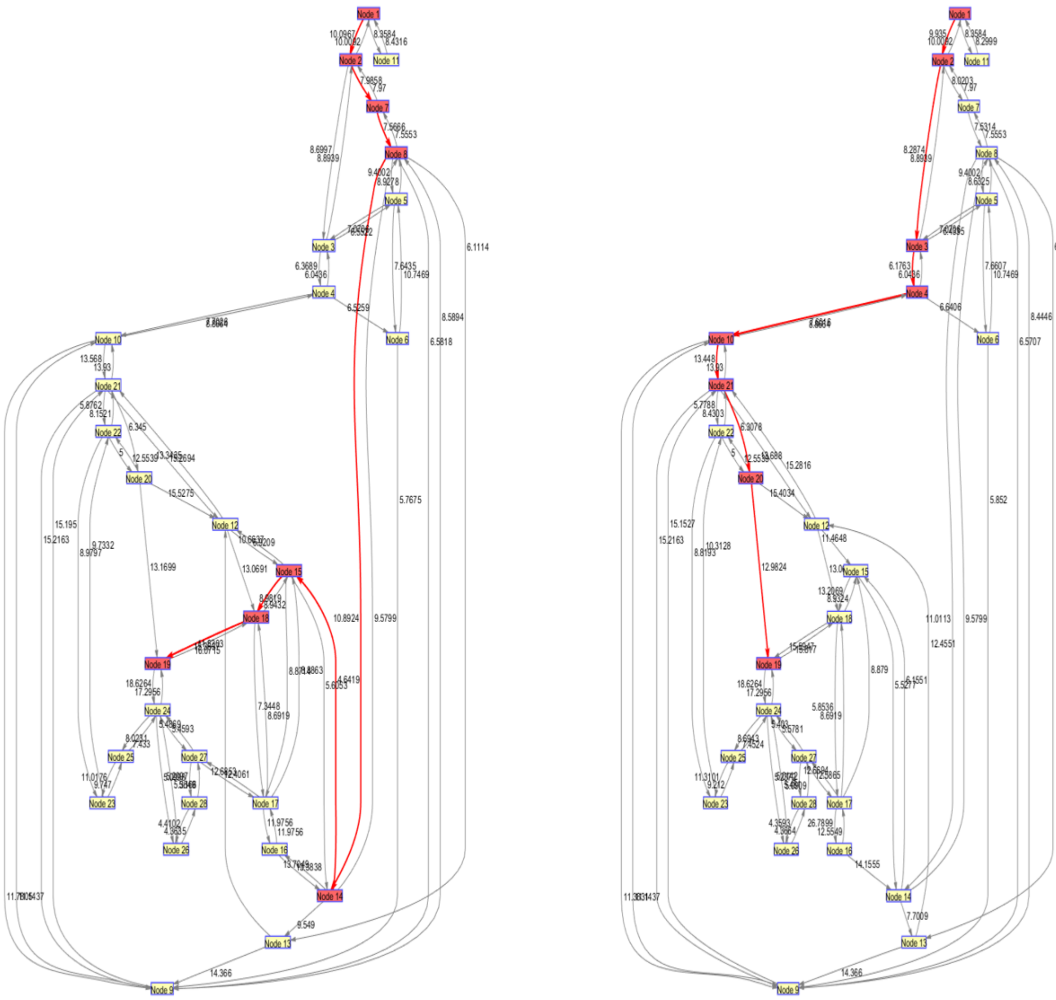


Figure 2: Here two topological representations of graph in Figure 1. For each link is reported the corresponding value of shortcut length W. In the left panel is showed in red the shortest path p_1 between node 1 and 19 for graph $\mathcal{G}(N = 28, E = 82, W)$. In the panel on the left, the links $15 - 12$, $15 - 17$, $14 - 16$ (one-way) have been removed and, again, in red is showed the surest path p_2 between node 1 and 19, that is the shortest path in $\mathcal{G}(N = 28, E = 79, W')$ considering the shortcut length W'.

Discussion and Conclusion

In this preliminary work, we studied a path measure and the associated route recommendation for drivers who prefer avoid situations in which they might remain stuck in the traffic without the possibility to take a good alternative path to arrive at their destination. This fact is very important and relevant in drivers behavior and with a more sophisticated traffic control system could decrease the bottleneck effect and decelerate congestion propagation in an urban network. This is because we might consider the problem of urban congestion deriving from two main factors: historical evidences and unpredictable events. In other words, we can expect that the congestion pattern is almost the same every day with peak hours in the morning and in the evening after work hours, and this is well studied and we can classify the recurrent congested phenomena as historical. Then we have car accidents or special events that have as consequence a sudden and dramatic drop of LoS of a link or a part of the city, and these are the unpredictable events.

In our Formula 2 we try to take into account both components by adding an estimated value of congestion based on historical (or simulated) probability and also the so-called shortcut centrality S, conveniently weighted by a Γ parameter.

The principle behind the computation of the sureness centrality is to simulate the case of an interruption or brutal drop of the LoS of each link and see the effects that this fact leads to all shortest paths length. By supposing that a driver will take probably the shortest path to travel from a point to another of the city, we compute the average loss of time in case that a determined link is not usable. Doing this for all links we have a property for each single link and we are not constrained to a path analysis, for example with random sampling, that would cost clearly more.

With a very efficient technique that we illustrated in section 3, we can easily define a new metric in the urban network and so, using the shortest path algorithm (for example Dijstra's one) we can highlight the surest path, that is the shortest path in the graph equipped with the sure length W. With the convenience measure in Formula 4 we use the additive property of the sure length and so we can easily compare paths also with different origin and destination. The distribution of this convenience measure $C_p^{O,D}$ (for different paths p and OD couples) can be useful to extract some general properties of a specific network or city. In particular, we can consider a normalized global average value $C_{\mathcal{G}}$ of different urban networks and study how their structures and complexity can influence congestion propagation. This can be seen in terms of giving to drivers a way to take good alternatives avoiding to overload a street in case of disruption, accident or sudden congestion phenomenon. In this direction, it could be interesting also study and compare in different cities the convenience measure $C_{\mathcal{G}}$ with the statistical data of such unpredictable events and their effect on traffic and simulate a scenario where the topology maximizes the global convenience in the city.

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