Robustness of Synthetic Traffic Networks Under Random Link Disruption

A. Espinosa Mireles de Villafranca, W. Wisetjindawat and R.E. Wilson

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Urban traffic constantly experiences disruption from exogenous sources such as the weather or roadworks. It is important to know what is the amount of disruption a network can sustain before reaching critical failure. To investigate this, we experimentally calculate the performance and robustness of simulated road networks when multiple links fail.

Previous studies of complex networks, for example [1], have shown that both network topology and the type of disruption play a role in a network's robustness, and not just its tolerance to failure, but to some degree the the manner of failure as well. As a particular example, scale-free networks are tolerant to random failure but vulnerable to attacks that target highly connected nodes. The mechanism for this is that network elements important for connectivity in Erdos-Renyi networks tend to be highly connected, therefore disruptions that affect these nodes have strong effects on network performance.

Road networks are often modelled as spatially embedded planar networks, for example in [2]. We take this approach as well, and although it limits the variance of node degree, there is alternative rich structure in the observables of our traffic systems — such as flows and system cost, see for example [3, 4] — that allow them to be studied as complex networks.

We contrast the differences in traffic patterns and network performance when networks suffer disruptions as opposed to operating in normal conditions. The performance of the road networks is probed by the total cost (mainly considered to be the aggregate of all drivers' journey times) by solving the *Static Traffic Assignment Problem.* Some structure of the traffic equilibrium is seen in the link-cost distributions and how they change as the magnitude of the disruption increases. The overarching motivation is that it could be useful to know the change in traffic patterns that networks exhibit as they approach critical failure, at the very least, as early-warning signals that the system is approaching collapse.

Our studies consider two different types of disruption:

- Links fail independently of each other.
- Links fail in a correlated way based on geographical proximity.

The first case serves as a control scenario of random noise that lends itself to be cast as a percolation problem — further details below. The second case reflects qualitatively different disruptions that reflect real-world events like flooding or earthquakes. We model the spatially-dependent disruptions (second case) by superimposing a disruption region (a disk) randomly on the network. Links (streets) that intersect this region are given a probability of failure based on the proportion of the street that is contained in the disk.

Our study is numerical in nature, so we take a statistical ensemble approach to guarantee some generality in our results. We synthesise large ensembles of random road networks from a family of random planar graphs, based on β-skeletons that we introduced at the Traffic and Granular Flow 2017 meeting. This road network model allows us to generate random networks by varying how grid-like the network is and by changing density of links. We compare the performance at the ensemble level to that of networks obtained by disrupting the networks.

In the simple disruption case, all links of a road network have an equal probability p of failing. This is equivalent to the standard bond percolation models on networks. We consider the percolation threshold to be the critical failure point of the networks. In the standard percolation model the critical point of the system can be defined as the expected value of p at which a connected network splits into multiple components. The transportation focus that we take means that we must study a slightly modified version of the problem in which destinations for journeys remain reachable from their origin. For simplicity, and in virtue of the fact that we average results over different instances of road networks in their respective ensembles, we consider networks with a single origin-destination pair.

Berche *et al.* ([5]) remark that the impact of disruption depends on the metric chosen to measure it. Hence we investigate a further metric that relates more closely to driver experience: the *average shortest path* connecting a single origin and destination pair whose routes traverse the network, or at least the largest remaining connected component of the network. This is measured by the travel time along this path using the *system optimal* assignment. Our preference for using SO as opposed to UE is due to the reasonable assumption that under unexpected disruption drivers cannot learn the condition of the network, but a system manager with knowledge of the state of the network could route vehicles such as to minimise the effects of link failure.

References

[1] Réka Albert, Hawoong Jeong, and Albert-László Barabási. Error and attack tolerance of complex networks. *Nature*, 406(6794):378, 2000.

[2] Alessio Cardillo, Salvatore Scellato, Vito Latora, and Sergio Porta. Structural properties of planar graphs of urban street patterns. *Physical Review E*, 73(6):066107, 2006.

[3] Steven J O'Hare, Richard D Connors, and David P Watling. Mechanisms that govern how the price of anarchy varies with travel demand. *Transportation Research Part B: Methodological*, 84:55–80, 2016.

[4] Hyejin Youn, Michael T Gastner, and Hawoong Jeong. Price of anarchy in transportation networks: efficiency and optimality control. *Physical Review Letters*, 101(12):128701, 2008.

[5] B. Berche, C. von Ferber, T. Holovatch, and Y. Holovatch. Resilience of public transport networks against attacks. *The European Physical Journal B*, 71(1):125–137, 2009.