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Dynamic clustering and propagation of congestion in heterogeneously congested urban traffic networks

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Abstract

The problem of clustering in urban traffic networks has been mainly studied in static framework by considering traffic conditions at a given time. Nevertheless, it is important to underline that traffic is a strongly time-variant process and it needs to be studied in the spatiotemporal dimension. Investigating the clustering problem over time in the dynamic domain is critical to better understand and reveal the hidden information during the process of congestion formation and dissolution. The primary motivation of the paper is to study the spatiotemporal relation of congested links, observing congestion propagation from a macroscopic perspective, and finally identifying critical pockets of congestion that can aid the design of peripheral control strategies. To achieve this, we first introduce a static clustering method to partition the heterogeneous network into homogeneous connected sub-regions. This method guarantees connectivity of the cluster, which eases the development of a dynamic framework. The proposed clustering approach obtains a feasible set of connected homogeneous components in the network called snakes, which represent a sequence of connected links with similar level of congestion. Secondly, the problem is formulated as a mixed integer linear optimization to find major skeleton of clusters out of this feasible set by minimizing a heterogeneity index. Thirdly, a fine-tuning step is designed to assign the unclustered links of the network to proper clusters while keeping the connectivity. The approach is extended to capture spatiotemporal growth and formation of congestion. The dynamic clustering is based on an iterative and fast procedure that considers the spatiotemporal characteristics of congestion propagation and identifies the links with the highest degree of heterogeneity due to time dependent conditions and finally re-cluster them while by minimizing heterogeneity and imposing connectivity. The developed framework can be directly implemented in a real-time framework due to its fast computation and proper integration of physical properties of congestion.

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Keywords: graph partitioning; congestion propagation; aggregate modeling; mixed integer linear programming; snake algorithm.

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1. Introduction

In traffic networks unlike other physical systems, humans make complex choices in terms of routes, destinations and time of travel, which create additional complexity to the system and difficulty in accurate prediction of link level traffic states, especially for real-time applications, like network-level traffic control. Moreover, transport in cities is governed by non-linear interactions with components (users, operators, infrastructure) that influence the system and vice versa. These components also adapt their behavior and decisions when the operators intervene in the system. Additionally, different network topologies and demand profiles affect the way congestion grows in space and time. Aggregated level network modeling has recently gained a lot of interest due to all aforementioned difficulties in traffic modeling at microscopic level.

The main characteristic of traffic in urban networks is that congestion is spatially correlated in adjacent roads and it can propagate with some finite speed in time and space. In fact, once a road gets congested, the probability of neighboring roads to be congested is higher than farther roads (i.e. congestion expands by propagating to neighboring roads). This spatial correlation of urban traffic congestion allows describing heterogeneous network as multiple relatively homogeneous and spatially connected regions Ji et al. (2014). This partitioning facilitates discovering the congested areas in an aggregated level. It also helps to observe well-defined Macroscopic Fundamental Diagram (MFD) relating space-mean flow and density in homogeneous areas of a city. The concept of MFD can be utilized in design real-time traffic control schemes specifically hierarchical perimeter control approaches to protect regions with high level of congestion and avoid gridlock conditions. While dynamic perimeter control for multi-region statically partitioned network has shown to decrease the level of congestion compared to traditional local traffic control strategies (see for example Ramezani et al. (2015)), more advanced techniques might be needed for networks with variant demand profiles. In this case, a dynamic clustering coupled with perimeter control strategies might be necessary. Dynamic clustering can also be important beyond the scope of real-time traffic control, as for example for planning studies, emission analysis, a dynamic user route information or even for advancing the operations of public transport systems.

The problem of clustering in urban traffic networks has been mainly studied in static framework by only considering traffic conditions at a given time. Nevertheless, it is important to underline here that traffic is a strongly time-variant process and it needs to be studied in the spatiotemporal dimension. Investigating the clustering problem over time help us understand and reveal the hidden information during the process of congestion formation and dissolution. The primary motivation of the paper is to study the spatiotemporal relation of congested links, observing congestion propagation from a macroscopic perspective, and finally identifying critical congestion regimes to aid the design of peripheral control strategies and improve mobility. This is not a straightforward task as transport networks despite spatial correlations in congestion are in principle heterogeneous due to road hierarchy and spatial distribution of demand. Thus, it is not always possible to treat congestion as a continuum in space. An example is directional flows towards a city center in the morning peak, where the same roads are highly congested in the one direction and uncongested in the other. The dynamic clustering framework will be capable of replicating how clusters expand or shrink in the process of congestion formation and dissolution. Moreover, it will be able to find new pockets of congestion and merge clusters with similar traffic conditions. In this framework, we will be able to chase where congestion originates and how traffic management systems affect its formation and the time it finishes. To achieve these goals, first we formulate the problem of partitioning networks to a desired number of regions as mixed integer linear optimization (a three-step framework). As it will be explained later, connectivity of clusters is explicitly enforced by imposing some constraints and the homogeneity of clusters is maximized in the objective function. In this framework, we can also specify characteristics such as compactness, size, *etc* for clusters.

There is a strong effort in the last 30 years for traffic flow models in one-dimensional traffic systems (see Helbing (2001) for an overview). With respect to network level, it has been observed with empirical and simulated data (see for example Geroliminis and Daganzo (2008), Buisson and Ladier (2009), Gayah and Daganzo (2011), Mahmassani et al. (2013), and many others) that a well-defined curve (MFD) exists between space-mean flow and density in networks with homogeneous traffic conditions. The idea of MFD has been re-initiated in Mahmassani et al. (1987) and Daganzo (2007) despite the first insight to the problem comes from Godfrey (1969) and Herman and Prigogine (1979). Analytical approximations of MFDs can be found in Laval and Castrillón (2015), Daganzo and Geroliminis (2008), Leclercq and Geroliminis (2013). Spatial heterogeneity in the distribution of congestion can significantly