Hierarchical control for large-scale urban road traffic networks

Conference Paper

Author(s):
Kouvelas, Anastasios; Geroliminis, Nikolas

Publication date:
2018-01-19

Permanent link:
https://doi.org/10.3929/ethz-b-000275970

Hierarchical control for large-scale urban road traffic networks

Anastasios Kouvelas and Nikolas Geroliminis[*]

Urban Transport Systems Laboratory
School of Architecture, Civil and Environmental Engineering
École Polytechnique Fédérale de Lausanne
[*]Corresponding author: nikolas.geroliminis@epfl.ch

Extended abstract submitted for presentation at the
7th International Conference on Transport Network Reliability (Sydney, 17-19 January, 2018)

1. Introduction

In the current work we focus on the development of hierarchical control structures to tackle the problem of signal control for large-scale urban networks. A recently developed perimeter control regulator, which integrates model-based optimal control and online data-driven learning/adaptation, is utilized for the upper-level layer. Another lower-level control layer utilizes the max-pressure regulator, which has been also proposed recently and constitutes a local feedback control law, applied in coupled intersections, in a distributed systems-of-systems (SoS) concept. Different approaches are discussed about the design of the hierarchical structure of SoS, i.e. mutual interactions between the two control layers, activation/deactivation of each layer, mutually related objectives of the regulators, online versus offline selection of critical intersection for the lower-level control layer. A hierarchical control approach that combines local and network level characteristics is expected to treat better uncertainties in demand and behavioural characteristics of drivers moving towards a more reliable performance of all users in the system.

A traffic microsimulation tool is utilized in order to assess the impact of each hierarchical control design to the overall traffic conditions. An urban network is simulated with a realistic OD matrix and different hierarchical control schemes are compared to the default signal settings that are currently used in the field. Each approach is also evaluated in comparison to a scenario of local distributed control in all the intersections or standalone perimeter control. Simulation investigations demonstrate the advantages of hierarchical control structures over different other disconnected regulator schemes. Preliminary results show that integrating a network-level approach within a local adaptive framework can significantly improve the system performance when spillback phenomena occur (a common feature of city centres with short links). An efficient multi-layer control design can significantly improve traffic congestion, leading to lower delays and higher production for the system. This has positive economic and environmental implications and large-scale cities are able to provide better quality of service to the users of the infrastructure.

2. Notations

The arterial network is represented as a directed graph with links $z \in Z$ and nodes $n \in N$. For each signalized intersection n, we define the sets of incoming I_n and outgoing O_n links. It is assumed that the offsets and the cycle time C_n of node n are fixed or calculated in real-time by another algorithm. In addition, to enable network offset coordination, it is quite usual to assume that $C_n = C$ for all intersections $n \in N$ but this is not the case here as the coordination problem is not considered. The signal control plan of node n (including the fixed lost time L_n) is based on a fixed number of stages that belong to the set F_n, wherein v_j denotes the set of links that receive right of way at stage $j \in F_n$. Finally, the saturation flow S_z of link $z \in Z$ and the turning movement rates $\beta_{i,w}$, where $i \in I_n$ and $w \in O_n$, are assumed to be known and can be constant or time varying.

By definition the constraint

$$\sum_{j\in F_n} g_{n,j}(k) + L_n = (or \ \leq) C_n \quad (1)$$

holds for every node n, where $k = 0,1,2,\ldots$ is the control discrete-time index and $g_{n,j}$ is the green time of stage j. Inequality in Equation (1) may be useful in cases of strong network congestion to allow for all-red stages (e.g. for strong local gating). In addition, the constraint

$$g_{n,j}(k) \geq g_{n,j,min}, j \in F_n \quad (2)$$

where $g_{n,j,min}$ is the minimum permissible green time for stage j in node n and is introduced in order to guarantee allocation of sufficient green time to pedestrian phases. The control variables of the problem are $g_{n,j}(k)$ and depict the effective green time of every stage $j \in F_n$ of every intersection $n \in N$.

3. Framework description

Figure 1 describes the basic principle of the hierarchical control framework. Basically, we have two distinct controllers that act independently, without communicating of exchanging information. At each control cycle (which is the same for both layers, e.g. 90 seconds) the controllers receive all the required measurements from the system and apply their equations. The two layers run in parallel and the decisions of each layer are not affected by the other. Each layer has its own objectives that are related to the global (upper) or the local (lower) performance of the network. They utilize different kind of input data (aggregated accumulations versus local queue measurements) and the green times that are calculated are applied to different signalised intersections. To this end, the intersections that are selected for the upper control layer (perimeter control) are excluded from the set of intersections to be studied for the application of the lower control method (max-pressure). The details of each regulator are explained in details in the next sections.

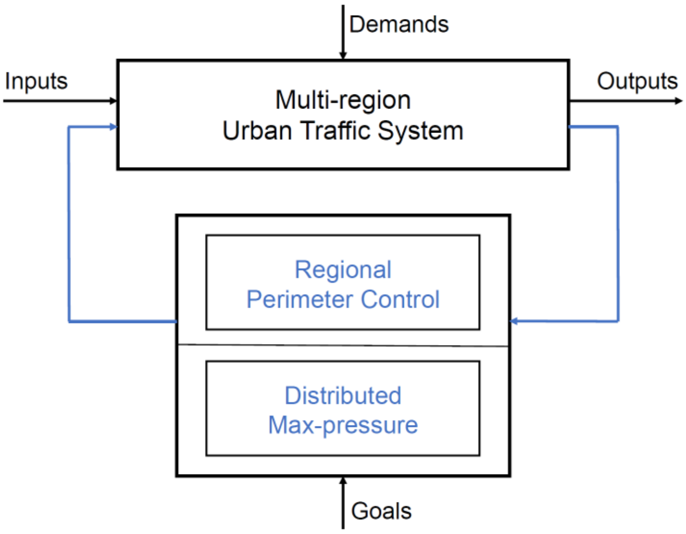

Figure 1: Hierarchical control framework

4. Upper level controller

For the upper control level (i.e. regional perimeter control) a multivariable feedback PI regulator from the literature is utilized. The regulator is introduced in Kouvelas et al. (2017) and controls the transferring flows between the antagonistic regions in an optimal way (i.e. so as to minimize the total delay of the system). Based on the distribution of vehicles in each region and an objective criterion about the total performance of the system one can regulate the flows that try to transfer from one region its neighbouring regions. The actuators are all the traffic lights that are located in the boundaries between regions and this can create inter-regional queues that affect the homogeneity of congestion. This is the reason that we apply here the lower level controller, i.e. to homogenise the traffic and improve the queues and congestion inside each region. Another work in the literature that utilizes similar perimeter control structures can be found in Ramezani et al. (2015).

5. Lower level controller

For the lower layer of the hierarchical framework the max-pressure control for arterial networks is introduced. This decentralized controller does not require any knowledge of the mean current or future demands of the network (in contrast to other model predictive control frameworks). Max-pressure stabilizes the network if the demand is within certain limits, thus it maximizes network throughput. However, it does require knowledge of mean turn ratios and saturation rates, albeit an adaptive version of max-pressure will have the same performance, if turn movements and saturation rates can be measured. It only requires local information at each intersection and provably maximizes throughput (Varaiya (2013)). Several variations of the basic method that can be applied in real-time (depending on the available infrastructure) are presented.

6. Results and conclusions

In the current work, we use as a case study network a replica of the city centre of Barcelona in Spain. For this network, we have a well calibrated microsimulation model in Aimsun (Figure 2), which is used for the simulation experiments. The purpose of the study is to run different control scenarios and investigate the effect of the controllers based on the statistics gathered from the microsimulation engine and empirical observations from the simulations (e.g. network load, traffic congestion, local gridlocks, etc.). Figure 2 presents the test network partitioned in 4 homogeneous regions. In this multi-region system perimeter control can be applied to regulate the inter-transferring flows between the regions. The methodology presented in the previous section is applied here. The perimeter controller acts on the intersections located in the boundaries of the network.

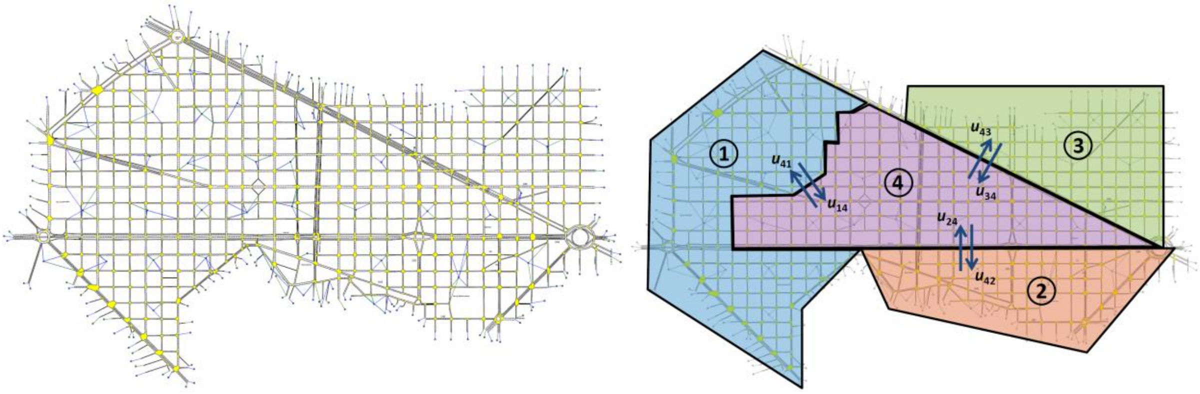

Figure 2: Microsimulation of the test network partitioned in 4 regions

In order to apply the lower level controller (max-pressure) the critical intersections of every region need to be selected first. In order to do so, we need a methodology to rank the intersections according to their importance and decide which are the most important. These intersections are controlled then based on the max-pressure control scheme that was described earlier. To this end we do an analysis of the simulation data for the fixed-time plan of the traffic lights. This scenario is called no control (NC) and it reflects all the pre-timed signal plans of the city of Barcelona. For this control scenario and for a realistic OD demand profile we run a replication and collect all the detectors data for occupancy and flow measurements. This data is a replication of what we can obtain in the real world and represent proxies of the network density and flow respectively.

Here, we utilize occupancy measurements by the detectors to estimate the number of vehicles that exist in every link of the network and thus calculate a proxy of the queue length. By summing up over all the input links of an intersection, we can perform an analysis of the level of congestion as well as the homogeneity of each intersection (which is actually analogous to the variance of the queues). If we perform this analysis to our data and we average over time we can get a good flavour of the importance of each intersection and how critical it is to the propagation of congestion in the network. The more congested an intersection is the more critical for the overall congestion. Also, in order for the perimeter control to be more effective, the traffic around an intersection needs to be as homogeneous as possible. A level of homogeneity is the variance of the queues for all the incoming links.

Figure 3 presents the results of this analysis. The x-axis represents the variance of all the queues around an intersection (averaged over time) and the y-axis the level of congestion for all the input links to the studied intersection (averages over space and time). Every point in these graphs represents an intersection, i.e. region 1 has 158, region 2 has 60, region 3 has 76, and region 4 has 227 intersections. These results refer only on the 1.5 hours of peak traffic and excluding the beginning and end of simulation where the traffic loads are very low. In these plot we are looking for outliers, i.e. intersections with high variance of queues, high level of congestion, or, alternatively with high values for both metrics.

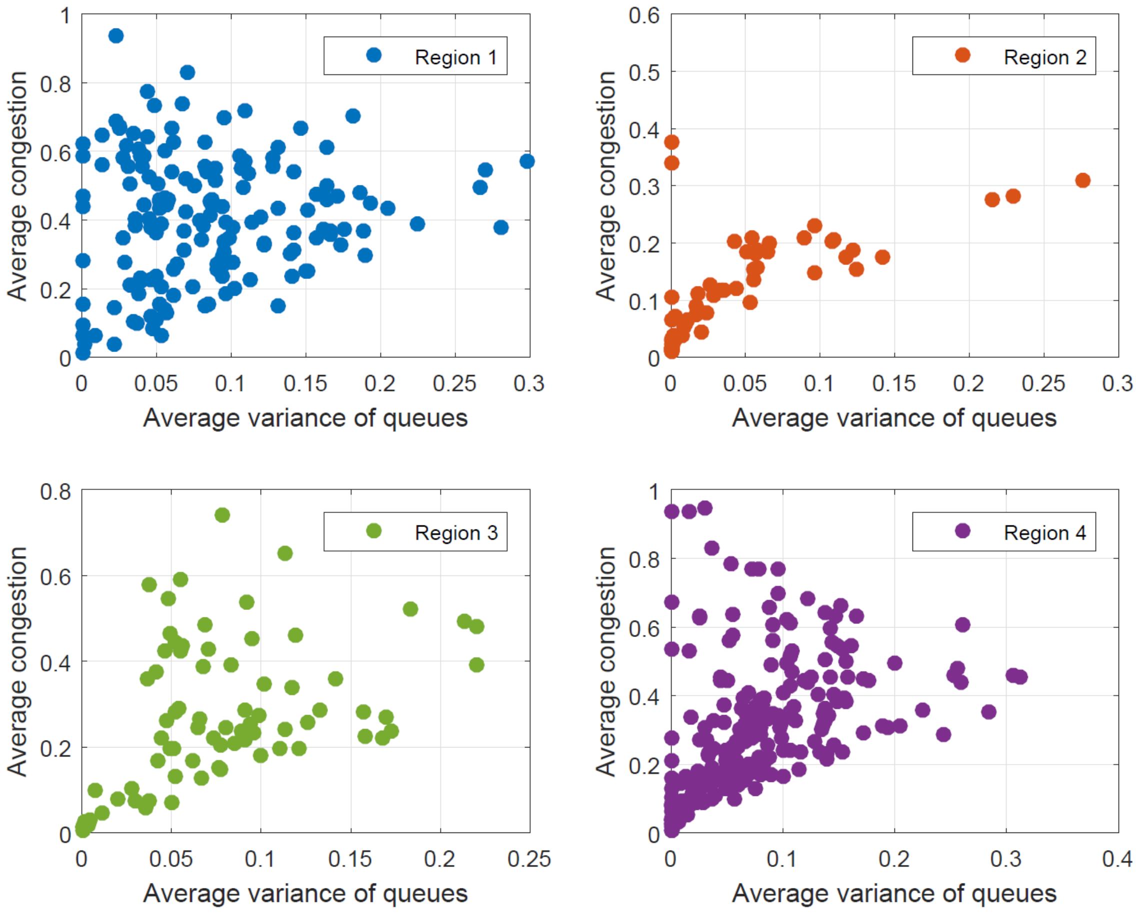

Figure 3: Analysis of the congestion and the queue variance for all the intersections of the network

References

Kouvelas, A., Saeedmanesh, M. and Geroliminis, N., 2017. Enhancing model-based feedback perimeter control with data-driven online adaptive optimization. *Transportation Research Part B: Methodological*, **96**, pp.26-45.

Ramezani, M., Haddad, J. and Geroliminis, N., 2015. Dynamics of heterogeneity in urban networks: aggregated traffic modeling and hierarchical control. *Transportation Research Part B: Methodological*, **74**, pp.1-19.

Varaiya, P., 2013. Max pressure control of a network of signalized intersections. *Transportation Research Part C: Emerging Technologies*, **36**, pp.177-195.