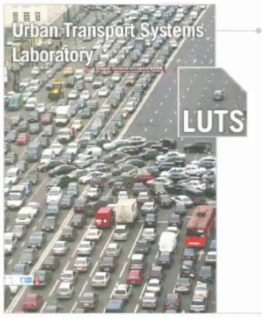
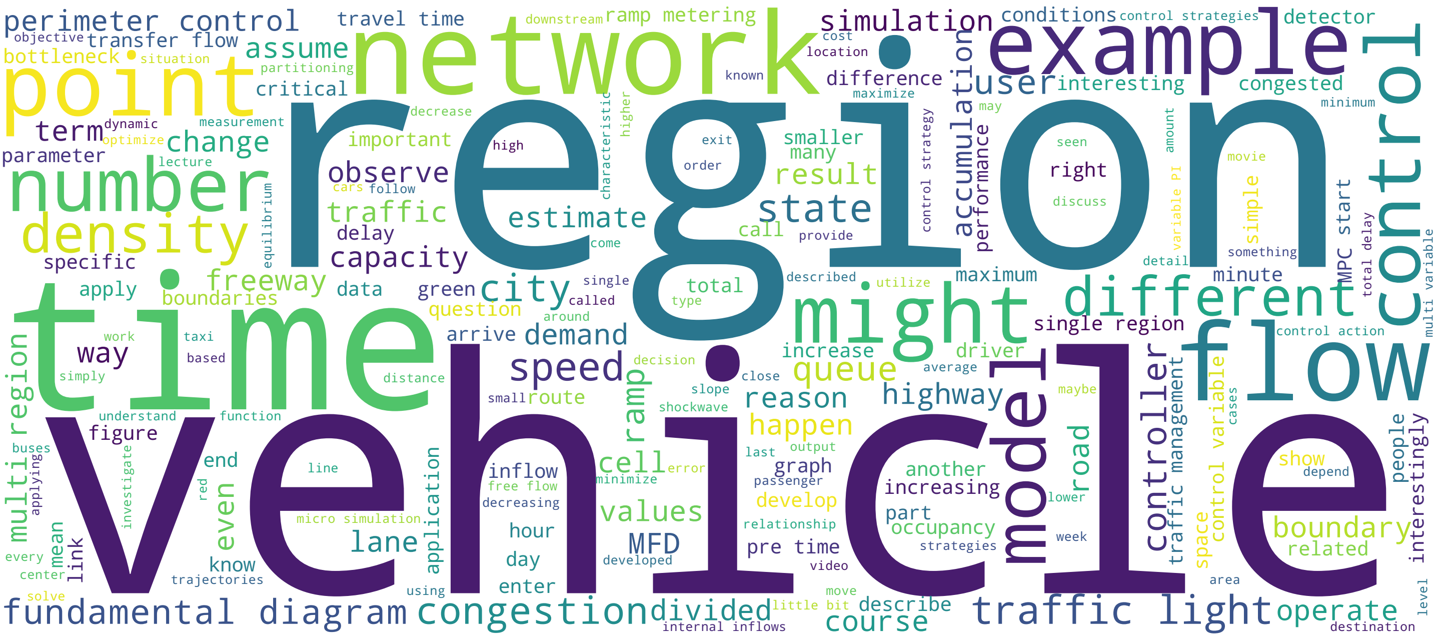
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Network-level traffic management and control with MFDs

Intro to traffic flow modeling and ITS

Prof. Nikolas Geroliminis

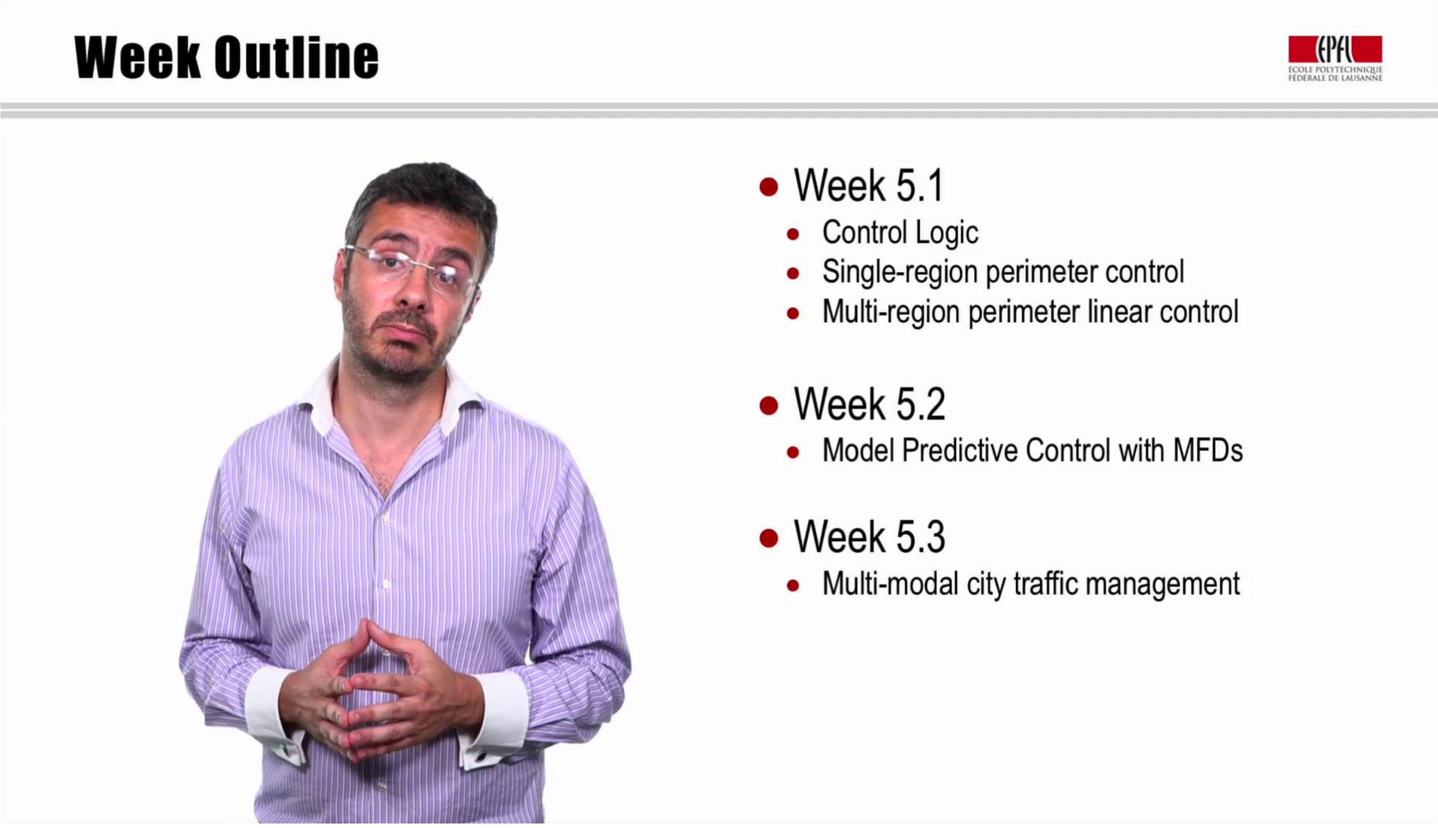




Search MOOC

Video

EPFL

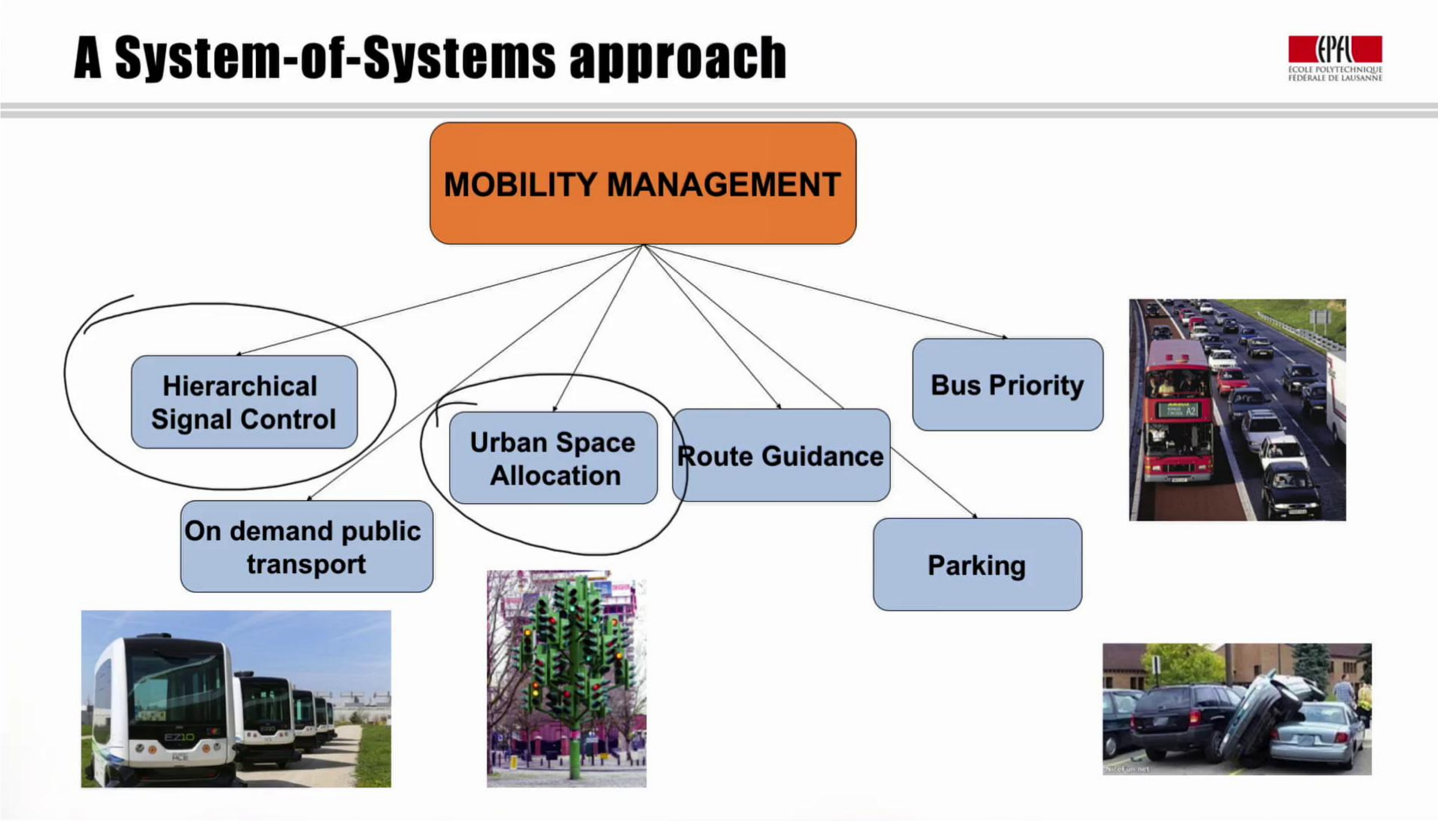


Welcome! Nowadays large cities are highly congested and there is no space to build new infrastructure in your roads. So improving mobility through traffic management looks like the visible solution. In this lecture we will investigate how we can use the concept of the microscopic fundamental diagram to integrate properly in traffic management. Here we see the outline of the course for this week. So we will first investigate what is the control logic to integrate MFD for traffic management. And we will do these for seeing and multi region systems. Later we will integrate a control strategy known as Model predictive control while later in this week we will see how we can develop traffic management schemes for multi-model networks.

Notes

Summary

0m 05s

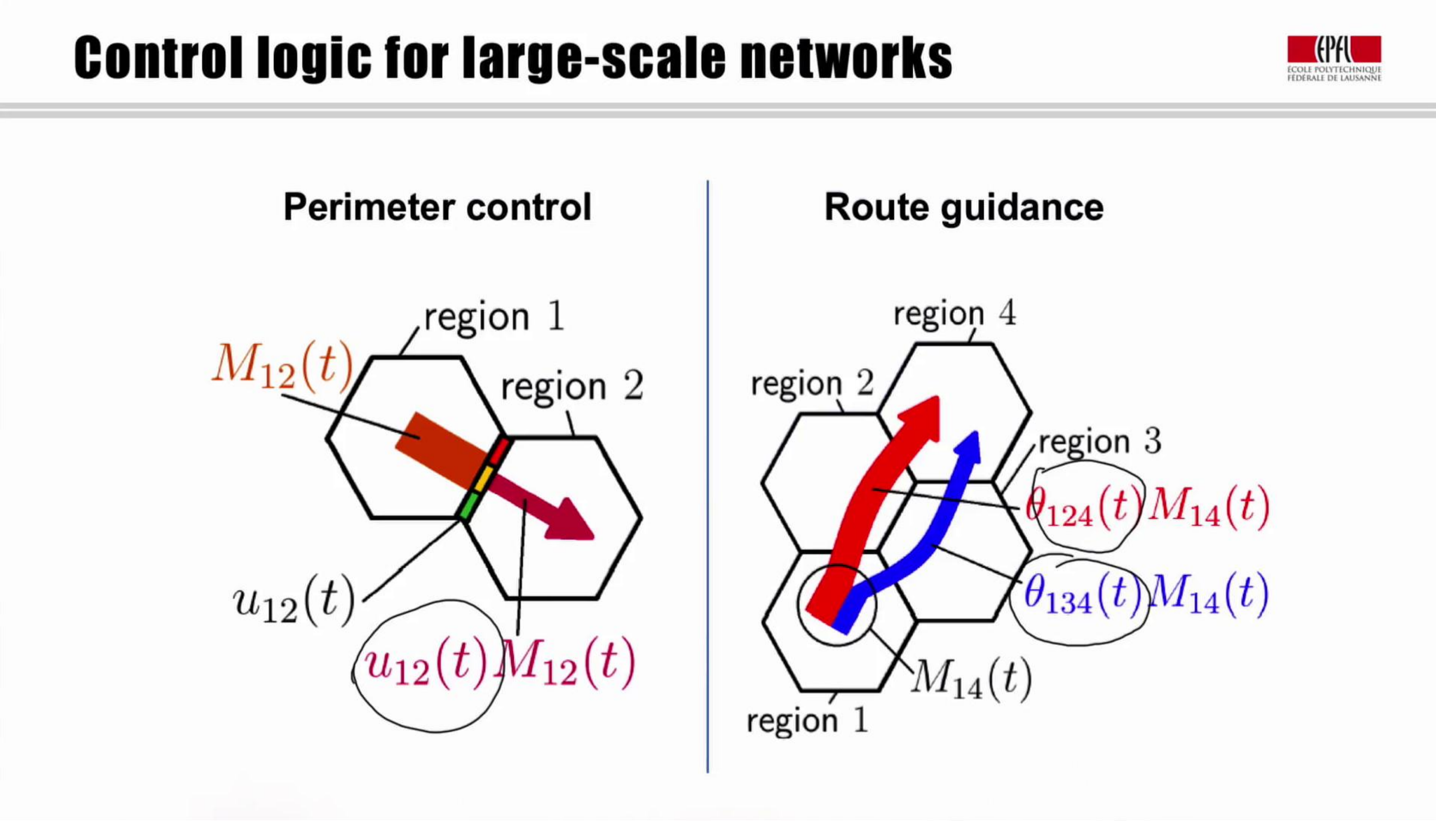


To improve mobility for large scale network with multiple modes of transport interacting for the same space. We have to utilize a system of systems approach. So generally we can look at different control strategies that are integrated together like hierarchical signal control or how to allocate the urban space between different modes how to provide priority for buses how to manage parking. How also to do road guidance or also have some new ways for on demand public transport. Integrating all these together is challenging. So here we will see in this course some examples of hierarchical signal control and urban space allocation. But we will also provide some references in the class material for the interested reader for the other strategies.

Notes

Summary

1m 00s



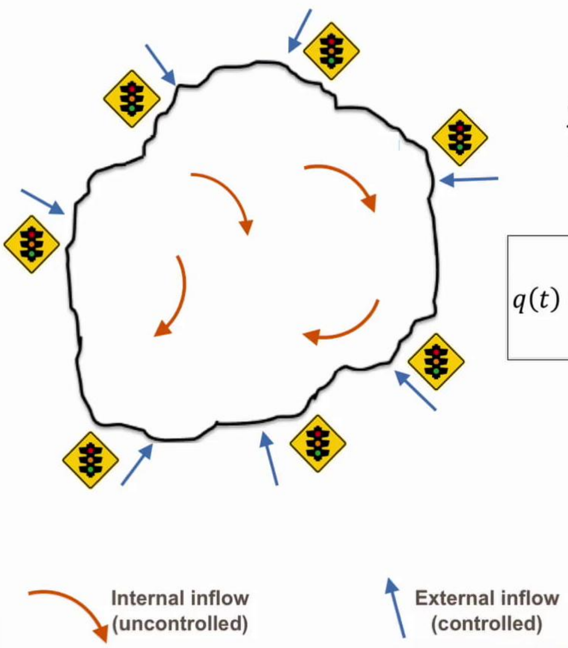
Let's look at the concept of the control logic for large scale networks. So recall for print from previous week that we might consider we have a city which is divided in multiple regions and we do. We want to develop perimeter control by controlling the transfer flows at the boundaries of the regions. So for example there is some transfer flow M12 that one to transfer from region 1 to region 2 by controlling the traffic lights and by increasing or decreasing the amount of green. And this can be expressed like with one term called u. We can influence how many vehicles are transferring from one region to another and if we do these for many regions in the network as a result we can minimize the total delays. But in some cases we might need to consider other strategies like route guidance. So here is an example imagine that there are some travellers that want to go from Region 1 to Region 4 and what we could do we could influence how these passengers are deciding to go through region 2 or through Region 3. So these thetas over here are some fractions where by using some optimization techniques we can estimate and we can provide guidance to the users so that by taking these routes the overall delays of this system becomes smaller.

Notes

Summary

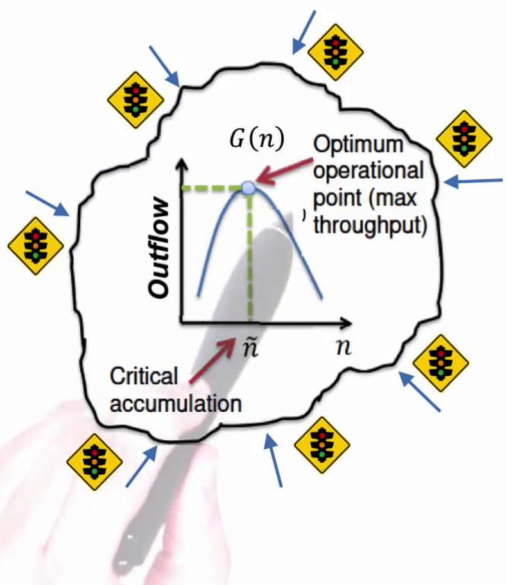
1m 53s

Single-region perimeter control



$$\frac{dn}{dt} = q(t) - G\big(n(t)\big)$$

$$q(t) = \begin{cases} q_{max} & if\ n(t) < \tilde{n} \\ q_{min} & if\ n(t) > \tilde{n} \\ G(\tilde{n}) & if\ n(t) = \tilde{n} \end{cases}$$



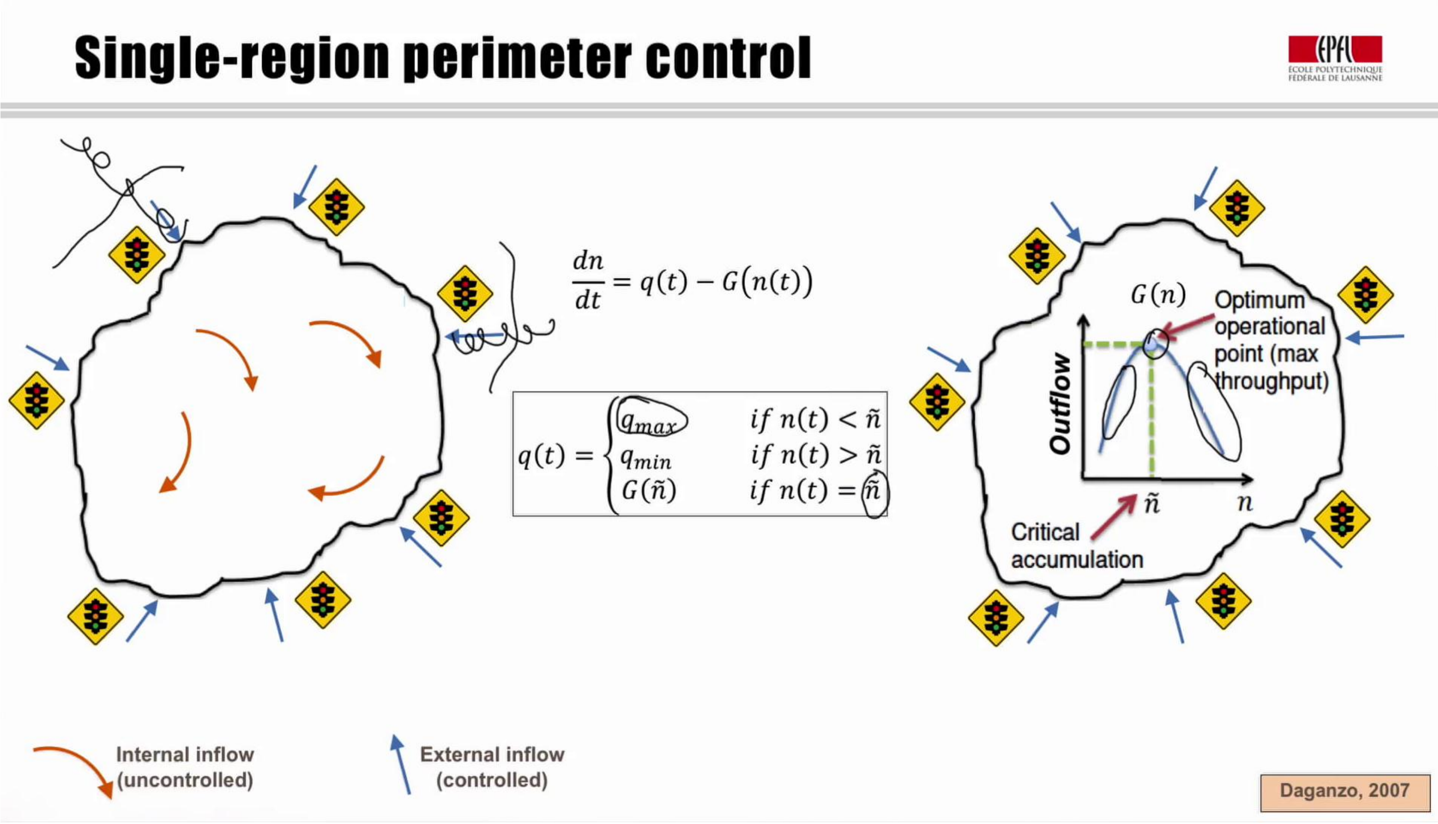
Daganzo, 2007

Let's look now at the simplest case where we want to develop perimeter control for a single region. Imagine that you have a single region of a city which traffic over there can be described by a macroscopic fundamental diagram. And there we have two types of flows. So we have internal inflows which are inflows generated by new vehicles that started their trips in the center of the city and we also have inflows that come from outside external inflows. So the internal inflows it cannot be controlled through perimeter control in the boundary and these are uncontrolled while the extent on inflows can be controlled by changing the traffic lights. So if we assume as I mentioned before that we have a memory for this region is not very difficult to prove that delays will be minimized if we are able to operate at the point where the outflow of the network is maximized. And in that case we can develop a single control which has been in control theories called like a bang bang control where the inflow will allow to enter in the system from outside is minimum if we are in the congested regime.

Notes

Summary

3m 26s



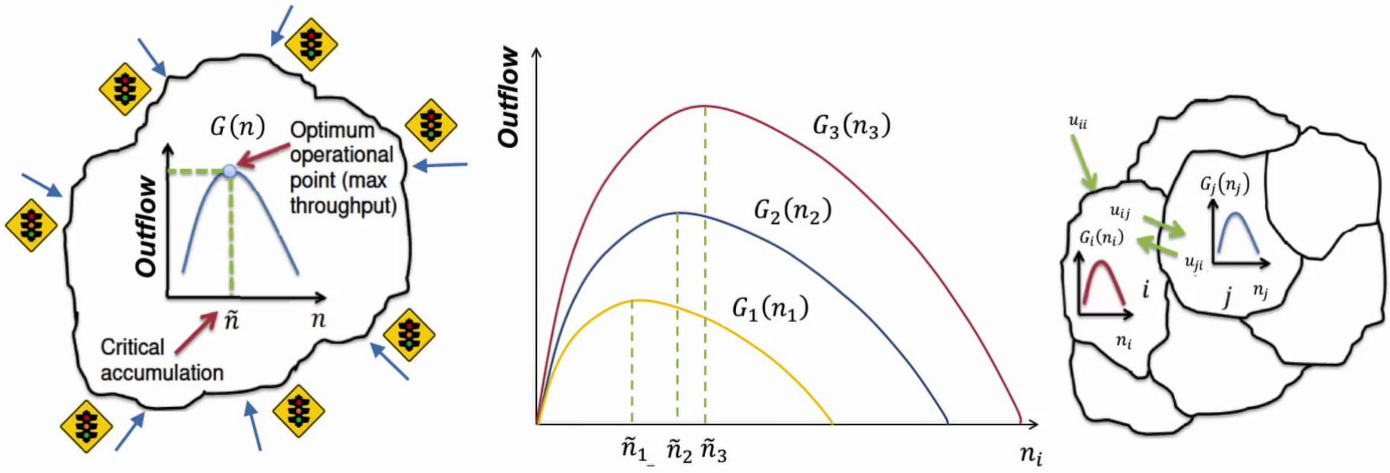
So if the number of vehicles is more than critical and is the maximum possible if we are in the uncontested regime and these qmin and qmax can be generated by also considering that there is some minimum and maximum green for specific directions in a traffic light. And if the system is n critical then our objective is to allow in the system to enter as many vehicles as they're able to exit, so G of n tilde which is the maximum outflow in the network. The result of this perimeter control will be that we might have queues that are generated in the boundary of the network and they are expanding. So in the single region case this is not a problem because all of the vehicles go in the center of the city but in cases that we have also external destinations this might influence movements that are happen in the periphery. So in that case we might need to consider more complicated perimeter control strategies.

Notes

Summary

4m 49s

Control logic: from single- to multi-region



WHY MULTI-region?

- heterogeneously congested cities with multiple pockets of congestion (partitioning)
- High internal inflows (controllability)
- Avoid long queues at boundaries (equity)

LUTS publications, 2012-2018

So let's see how we can control multi region networks. So please recall that if you have a heterogeneous city by applying some clustering technique we can divided in a different rabin of a number of regions where its region will have a well-defined MFD. So, now our control actions is that we can actually control the inter transfer between different regions. These are the terms uij that we have here but we can also control the number of vehicles that are entering from the external boundaries of the city let's call them uii. Some interesting question we need to answer is why we need to have a multi-region perimeter control. The first reason is that cities can be principally heterogeneous congested with multiple pockets of congestion so partitioning is necessary. Another reason is that in the single region case we might have very high internal inflows. So in that case we might not be able to control the system in the solution there by doing it clustering is that the internal inflows would be smaller for the individual regions. So we have a stronger control authority to control transfer flows. And the last reason is that we want to avoid long queues at the boundaries. And this is related with equity because we would like to treat all travellers in the city in a way that they all experience a similar level of congestion.

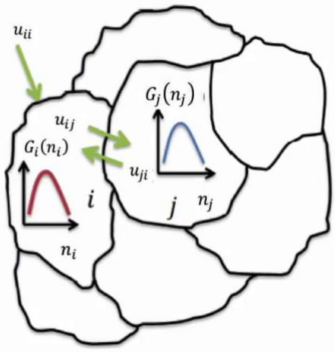
Notes

Summary

5m 59s

Multi-region perimeter control (LQI control)

- **Given:** MFDs for each reservoir $G(n)$
- **Observe:** Accumulation $n_j(t)$
- **Control:** Boundary flows and external inflows
- **Maintain** Throughput Optimal Operational Point



- **Linear-Quadratic-Integral control** (multivariable PI-regulator)

$$\mathbf{u}(k) = \mathbf{u}(k-1) - \boxed{\mathbf{K}_\mathrm{P}}\,[\mathbf{n}(k) - \mathbf{n}(k-1)] - \boxed{\mathbf{K}_\mathrm{I}}\,\left[\mathbf{n}(k) - \boxed{\hat{\mathbf{n}}}\right]$$

- $\mathbf{u}(k)$: control vector of $u_{ij}(k), \forall i \in \mathcal{N}, j \in \mathcal{N}_i$
- $\mathbf{n}(k) \in \mathbb{R}^N$: state vector of region accumulations $n_i(k), \forall i \in \mathcal{N}$
- $\hat{\mathbf{n}} \in \mathbb{R}^N$: vector of the set points $\hat{n}_i$ for each region i
- $\mathbf{K}_\mathrm{P}, \mathbf{K}_\mathrm{I}$: proportional and integral gains.

Aboudolas & Geroliminis, 2013

So let's become a little bit more technical and let's look at some controlled methodology for multi-regional cities. So let's assume that we have the MFDs for each region or there is a reservior G of n. Let's say that by using different sensors were able to observe the accumulation the number of vehicles for each region at different intervals and then what we will do we will control the boundary flows and then the external inflows by changing the traffic lights over there and the control variables there are uij and uii. So there is some known methodology known as Linear Quadratic integral control where once you define some set points some critical values of accumulation that we would like to control each city then we can develop a controller which strives to succeed this goal. And this is controller is given by this equation. The theory behind this is that once we have nonlinear system with non-linear dynamics and we defined the set points we can linearized the system around the set points and we have an objective function that we try to minimize some terms and then by solving a ricatti equation who can identify what are the proper parameters to develop this controller.

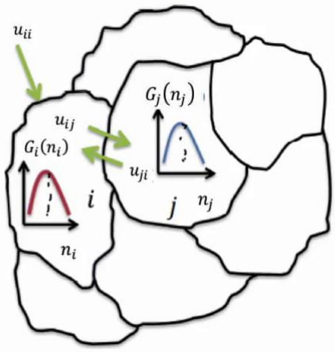
Notes

Summary

7m 37s

Multi-region perimeter control (LQI control)

- **Given:** MFDs for each reservoir $G(n)$
- **Observe:** Accumulation $n_j(t)$
- **Control:** Boundary flows and external inflows
- **Maintain** Throughput Optimal Operational Point



- **Linear-Quadratic-Integral control** (multivariable PI-regulator)

$$\mathbf{u}(k) = \mathbf{u}(k-1) - \boxed{\mathbf{K}_\mathrm{P}}\,[\mathbf{n}(k) - \mathbf{n}(k-1)] - \boxed{\mathbf{K}_\mathrm{I}}\,[\mathbf{n}(k) - \boxed{\hat{\mathbf{n}}}]$$

- $\mathbf{u}(k)$: control vector of $u_{ij}(k), \forall i \in \mathcal{N}, j \in \mathcal{N}_i$
- $\mathbf{n}(k) \in \mathbb{R}^N$: state vector of region accumulations $n_i(k), \forall i \in \mathcal{N}$
- $\hat{\mathbf{n}} \in \mathbb{R}^N$: vector of the set points $\hat{n}_i$ for each region i
- $\mathbf{K}_\mathrm{P}, \mathbf{K}_\mathrm{I}$: proportional and integral gains.

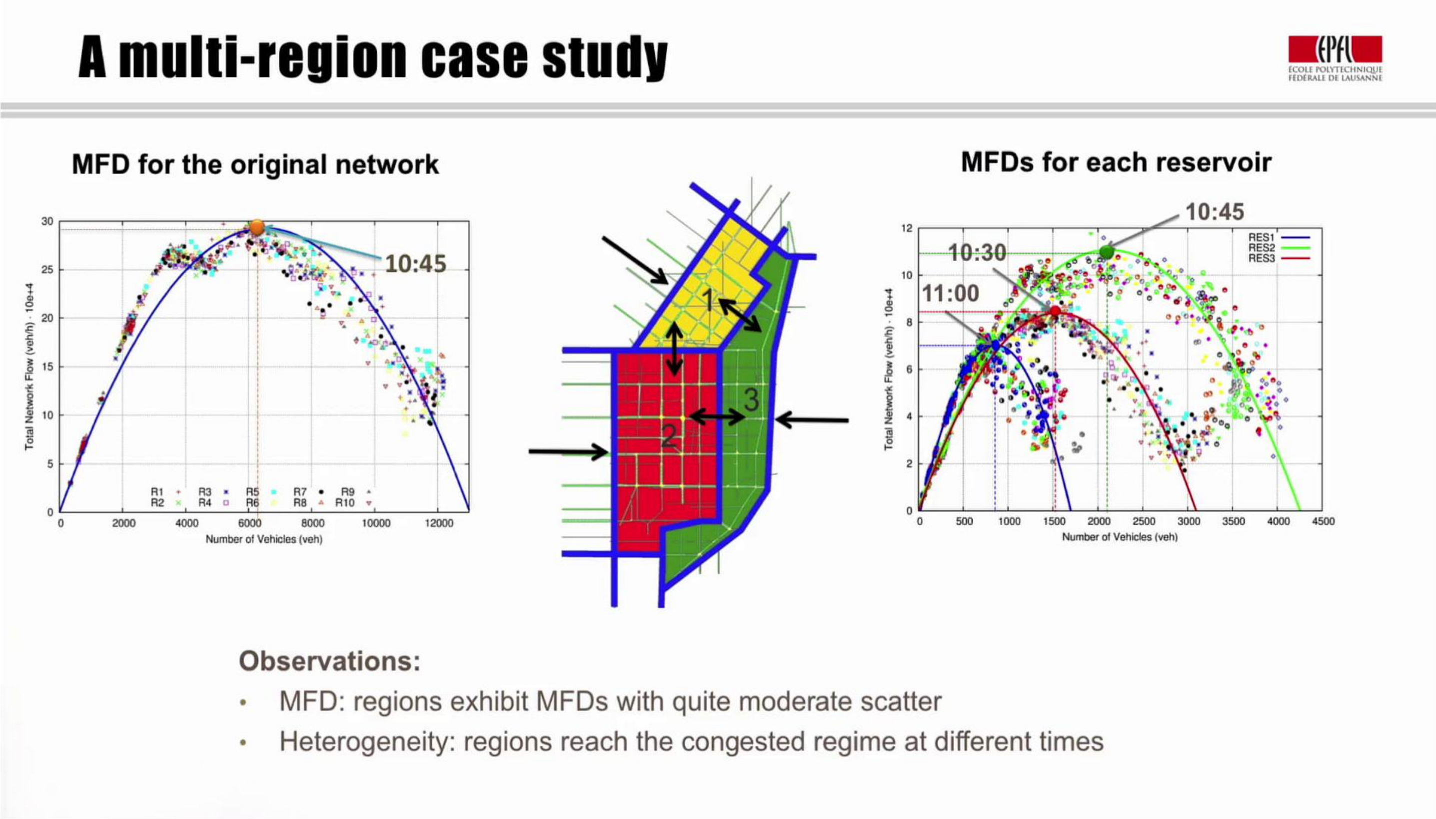
Aboudolas & Geroliminis, 2013

So let's see how this controller looks like. So K is the interval is time. So the amounts of vehicles were allowed to transfer from one region to another. Depends on the decision we had at the previous time u(k – 1). And then we have two terms; the one term, the integral term is related on what is a state of the system with respect to their critical accumulation the set point which for example in this case is the value that maximizes the flow. The second term which is the proportional term is how fast the dynamics of the system. So actually this is a classical multivariable to be a regulator which has applications in many different physical systems in aerospace engineering so it can be used on how airplanes are flying or even in everyday life activities. So for example the air conditioning it operates by using similar type of controllers.

Notes

Summary

9m 09s

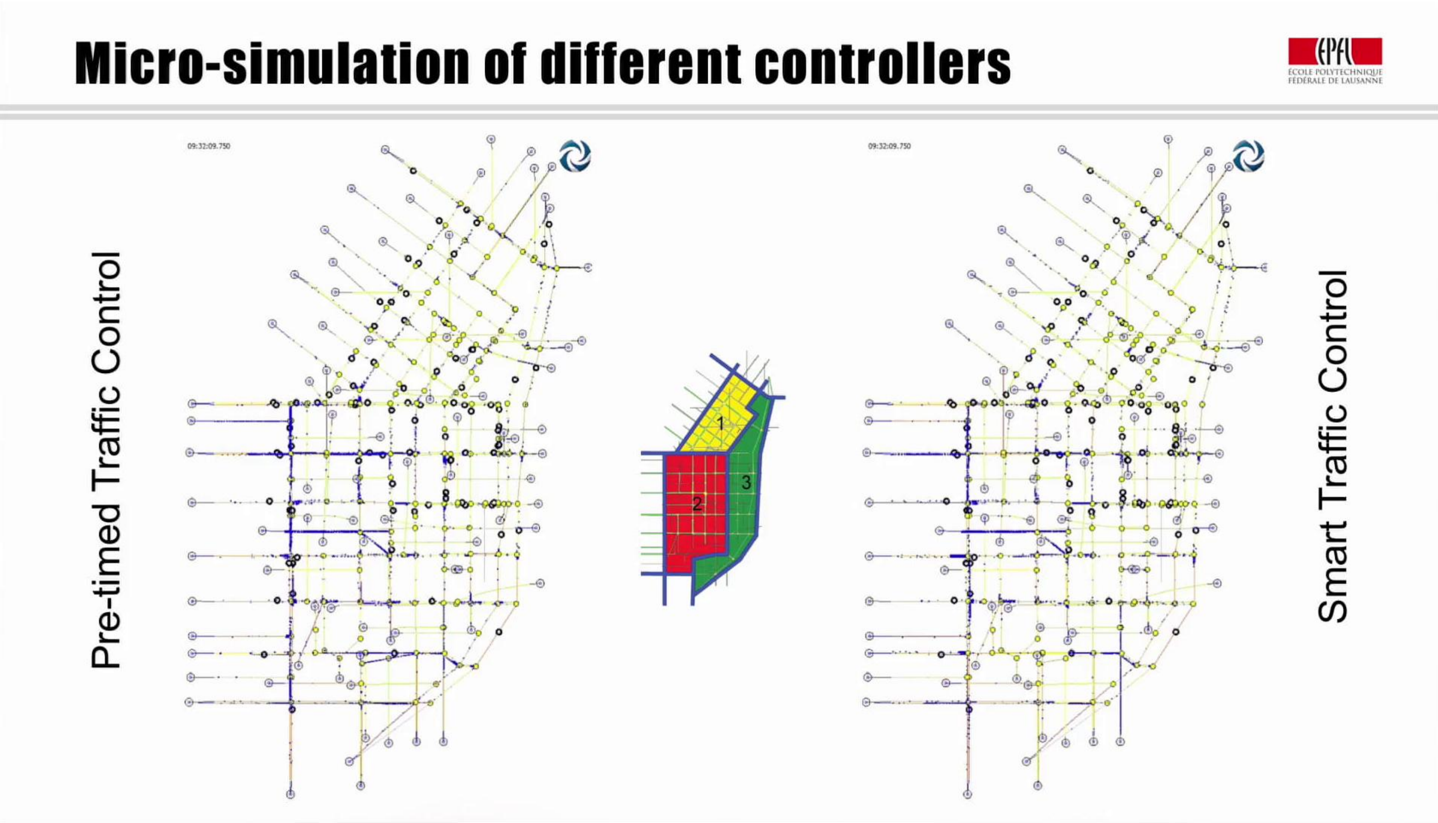


So let's see an application of this control through a multi-region case study. So here we use again the micro simulation of San Francisco where after partitioning we divided in three regions as seen in this figure and the black arrows shows the point where we control the inter transfers between the different regions. So here we have three internal and three external control variables. Interestingly after partitioning what we see we see that each region has a well-defined MFD with moderate scatter. But what is also interesting is that its region reaches the congested regime at different times so it's very important to do a multi-region perimeter control because if we control the system by using a single region and if d what we see we see that the performance will be lower.

Notes

Summary

10m 19s



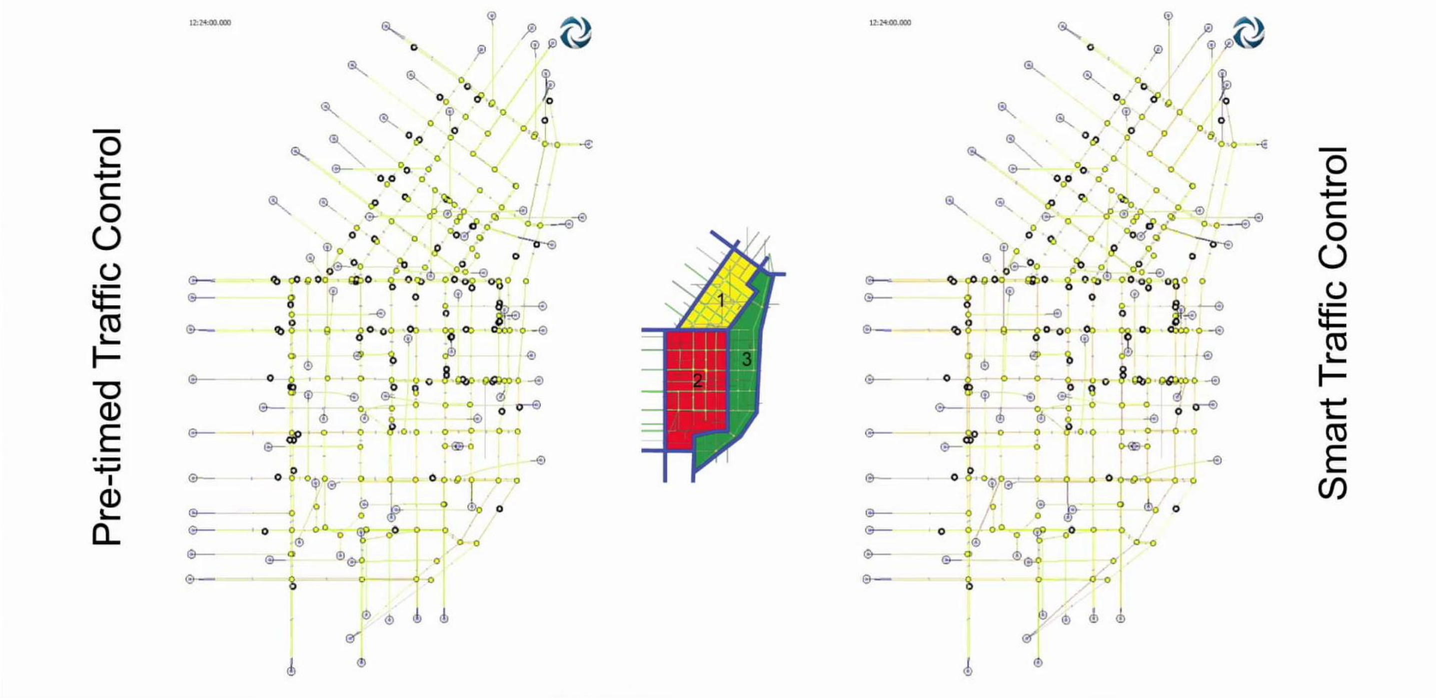
As mentioned before here with blue lines are the boundaries where the traffic lights in these boundaries will change and b be part of their perimeter control strategy. So when the movie starts we will see how vehicles are moving and for each hour we will see in details. The first one or two minutes and then the movie will move forward fast to the next hour. And on the left we see the three time traffic control well on the right. We will see there's more traffic control which is developed. Let me also mention to you that in this network we have approximately 100 traffic lights and we only decide to change around 15 or 20 that are in the boundary. So in the beginning the two movies are identical because there are only a very few vehicles moving around. And as the demand now the controller is not active. So the traffic lights are appearing as pre time and the demand increases. So what will happen soon? What we will see that more vehicles will move around. So here is a time where we start seeing long queues. And actually this is the time we start seeing some differences and the controller is active. So what I would like to draw your attention is that we see queues in both boundaries of the network.

Notes

Summary

11m 14s

Micro-simulation of different controllers



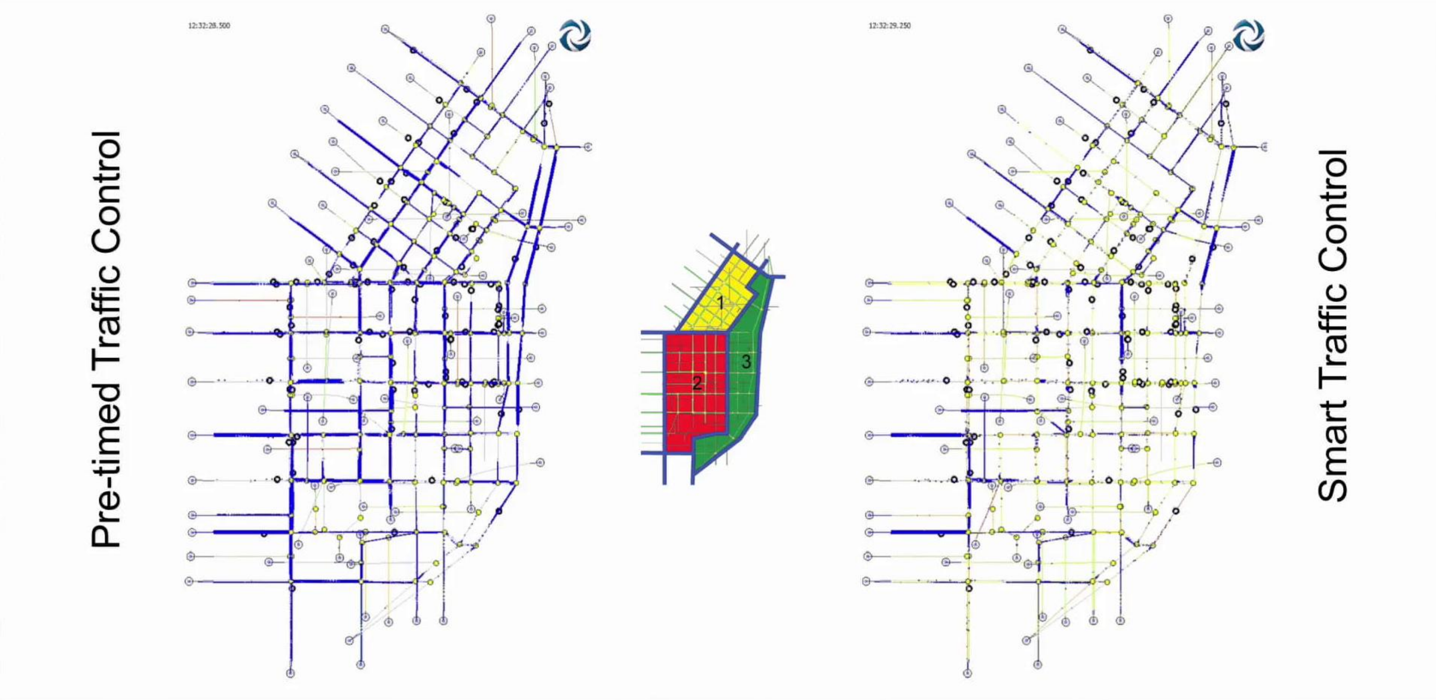
But please note that these queues are because of Spielberg. So because of vehicles downstream that block the movements of upstream vehicles while in that case these queues over here happened because of perimeter control as after these vehicles are stopped for some time they are able then to enter the network and travel very fast.

Notes

Summary

12m 36s

Micro-simulation of different controllers



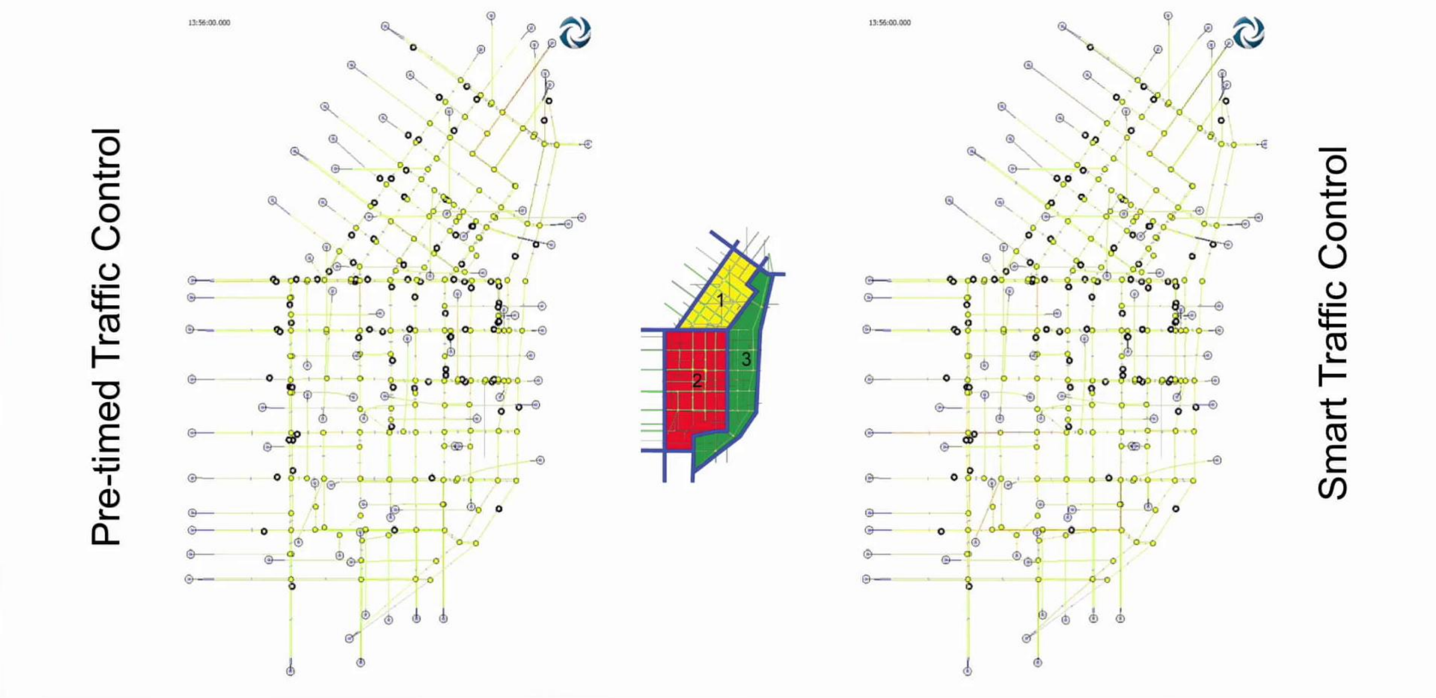
So clearly the center of the network here is much less congested compared to the centre of the network there and actually these regions operate very close to capacity and as the simulation continues we see that in pre time case we reach almost a state of gridlock with growing queues everywhere in the network while in the smart control we only have some queues in the boundary.

Notes

Summary

13m 04s

Micro-simulation of different controllers



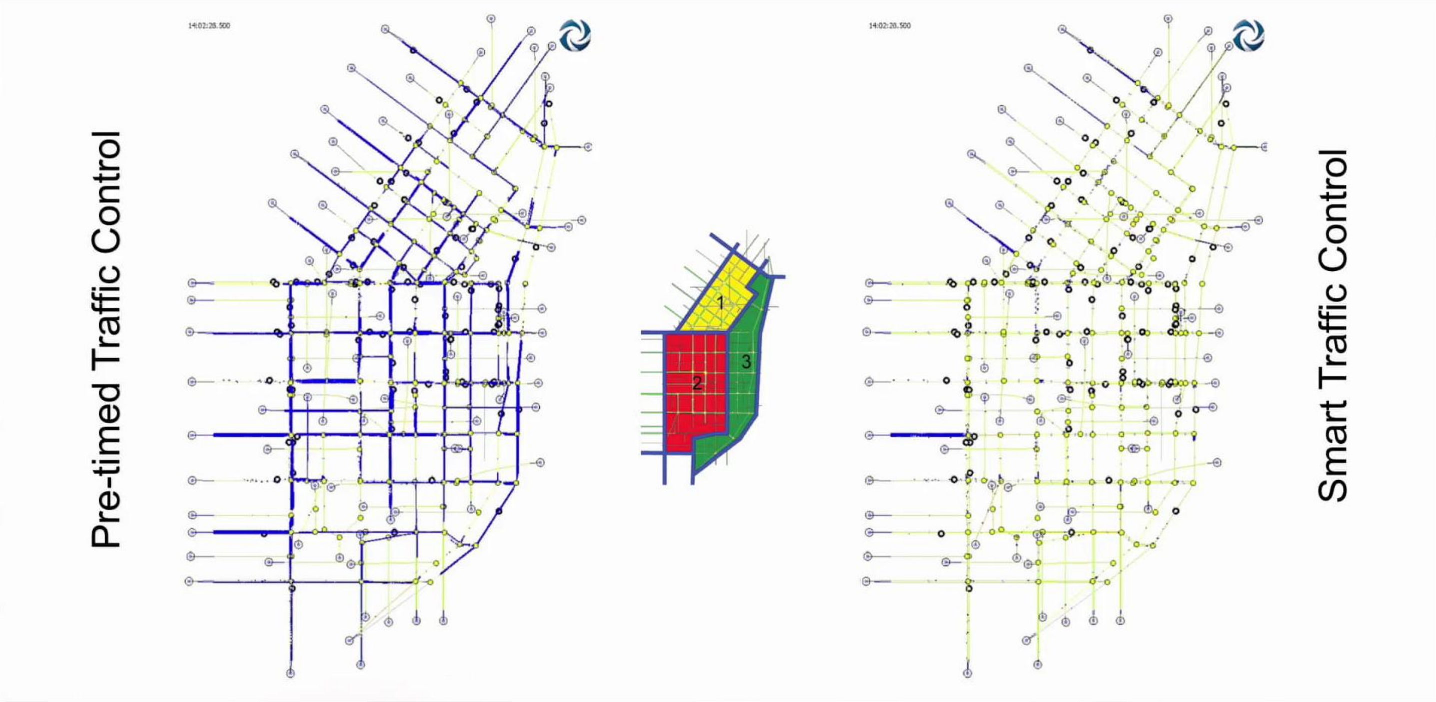
But a point I would like to make is that in this control strategy we have a win win situation for all user.

Notes

Summary

13m 23s

Micro-simulation of different controllers



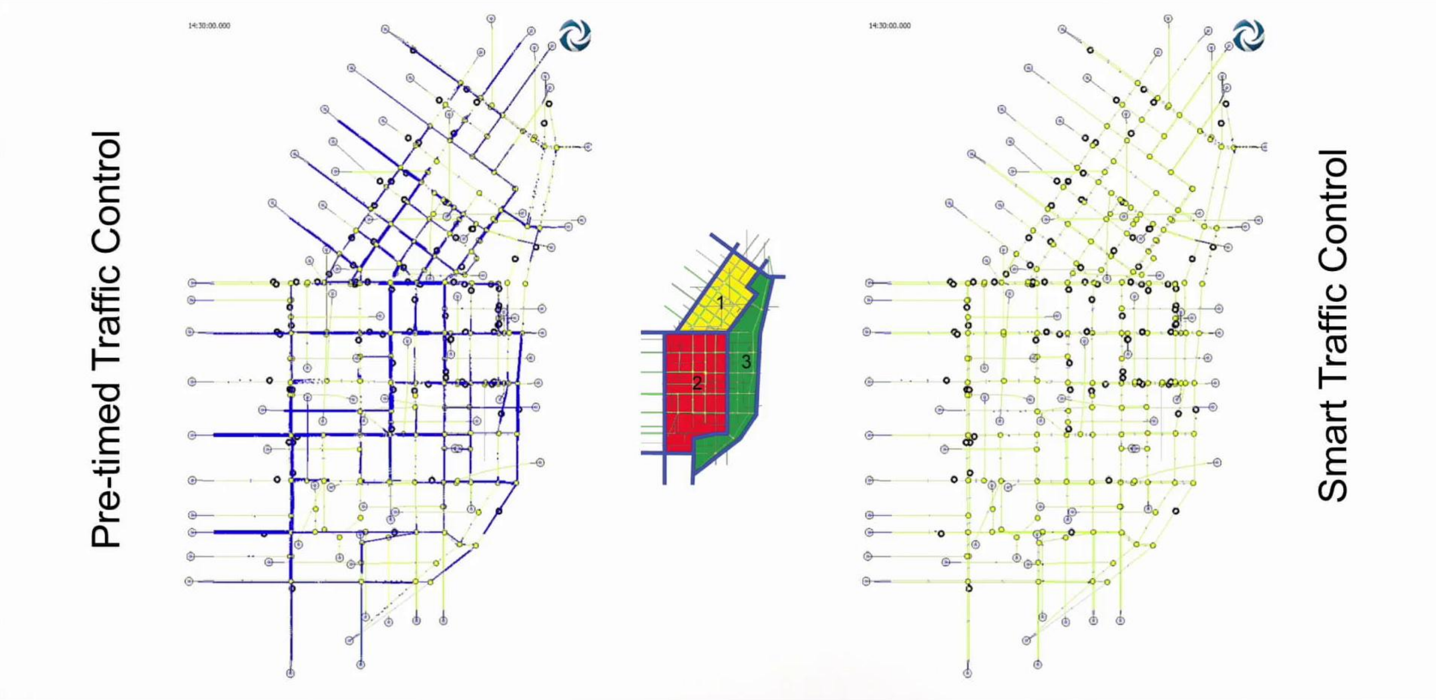
So even the users that are delayed and restricted in the boundary of the network and we do that by increasing the red faces of traffic lights towards the center.

Notes

Summary

13m 29s

Micro-simulation of different controllers



Even if these users will arrive to their destination faster compared to no control and the reason is simple is because even if these vehicles have to wait for additionally some seconds or maybe one minute when they enter the network they will go much faster because the network operates at capacity and the speed of it here might be 20 kilometers per hour well over there might be close to zero. So this is known in the literature slower is faster effect.

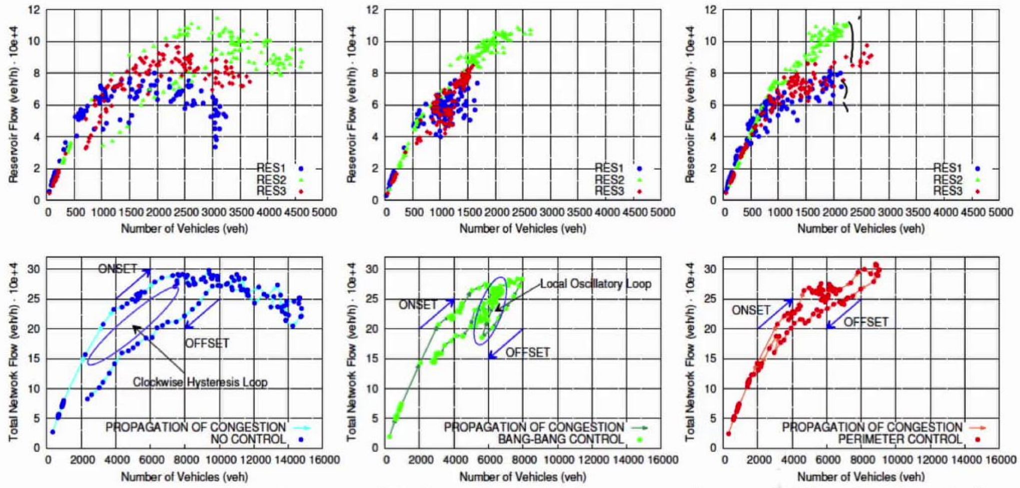
Notes

Summary

13m 45s

Comparison of controllers

- Comparison with pre-timed fixed signals: improvement 33% for total travel time
- Comparison with Bang-bang control: Improvement 12%
- Multi-region PI: maintains throughput; respect reservoirs' homogeneity



Pre-timed fixed signals **Single-region Bang-Bang control** **Multi-region PI control**

So let's see some results by comparing mainly three different controllers. The one is the pre time fix signals where we don't change the amount of green per face with the time of the day. The second one a single region bang bang control as it was described in the previous slides of this presentation. And the last one is the multi region multi variable PI control that we developed. So first of all in this graph we see the M of these for it's region and what we see we see that all regions become significantly congested and also we have a strong clockwise hysteresis loop in the total network flow. If we see now in the case of bang bang it's interesting that none of the regions enters the congested regime but actually because we called the control only a single region we see that reservoir 1 and reservoir 3 are very uncongested so they operate at values less than the maximum flow. And for this reason we also observe some oscillatory behavior in the MFD during the onset and in the offset. In the best case of the multi region PI controller that has an improvement of around 30 percent with respect to the total travel time. We see that all the regions are able to operate almost at the critical point.

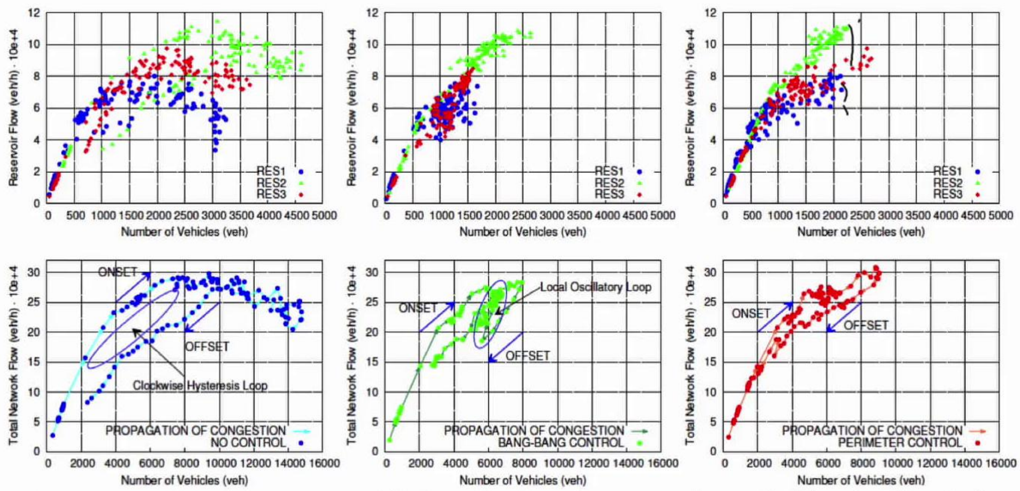
Notes

Summary

14m 12s

Comparison of controllers

- Comparison with pre-timed fixed signals: improvement 33% for total travel time
- Comparison with Bang-bang control: Improvement 12%
- Multi-region PI: maintains throughput; respect reservoirs' homogeneity



Pre-timed fixed signals **Single-region Bang-Bang control** **Multi-region PI control**

And what we also see we see that we're able to observe higher total network flows compared to the other cases and as a result having less delays in the vehicles are able to arrive to their destination faster for our all region. So we have Win-Win effects.

Notes

Summary

15m 42s

A more advanced controller (PI + parameter fine tuning)

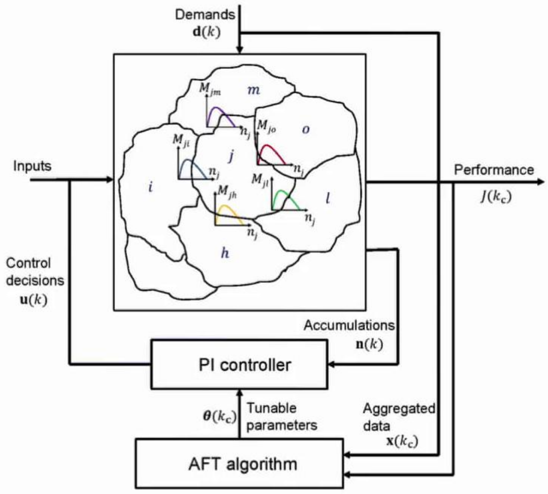
(a) Model-based multivariable PI regulator

$$\mathbf{u}(k) = \mathbf{u}(k-1) - \boxed{\mathbf{K}_\mathrm{P}}\,[\mathbf{n}(k) - \mathbf{n}(k-1)] - \boxed{\mathbf{K}_\mathrm{I}}\left[\mathbf{n}(k) - \boxed{\hat{\mathbf{n}}}\right]$$

- $\mathbf{u}(k)$: control vector of $u_{ij}(k), \forall i \in \mathcal{N}, j \in \mathcal{N}_i$
- $\mathbf{n}(k) \in \mathbb{R}^N$: state vector of region accumulations $n_i(k), \forall i \in \mathcal{N}$
- $\hat{\mathbf{n}} \in \mathbb{R}^N$: vector of the set points $\hat{n}_i$ for each region i
- $\mathbf{K}_\mathrm{P}, \mathbf{K}_\mathrm{I}$: proportional and integral gains.

(b) Data-driven online adaptation

- At each iteration, AFT algorithm receives
  - the measured performance index J (total delay of the system)
  - the measurable external disturbances $\mathbf{x}$ (aggregated demand)
- Using the samples of the measured quantities AFT calculates new tunable parameter values to be applied at the next iteration.



AFT: automatic fine tuning

Kouvelas, Saeedmanesh & Geroliminis, 2017

Let's now consider a more complicated case it might not be possible to operate all regions at the critical value of density that maximizes the flow. The reason is that for example if we have a city centre which is highly congested and we want to restrict the inflow. This might have as a result that other regions of the city become more congested. So in that case we might decide to operate for example the city centre at the critical value while some other parts of the city might need to operate at some states that are a little bit more congested. But the question is how more congested. So in that case we might develop a similar multi variable PI regulator but the difference of it here now is that their gains KP and KI but also the set points for each region might be different. And then we cannot utilize our previous approach to determine these values. So in this work which is a joint collaboration between myself rather than Anastasios Kouvelas we combine a multivariate PI regulator with an online adaptive scheme that we use to determine which are the ideal values of these parameters.

Notes

Summary

16m 01s

A more advanced controller (PI + parameter fine tuning)

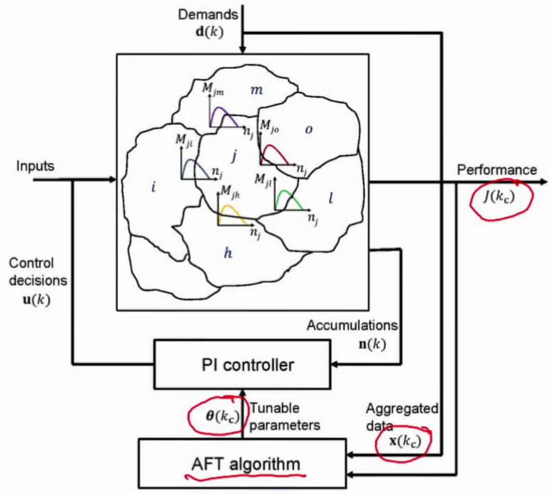
(a) Model-based multivariable PI regulator

$$\mathbf{u}(k) = \mathbf{u}(k-1) - \boxed{\mathbf{K}_\mathrm{P}}\,[\mathbf{n}(k) - \mathbf{n}(k-1)] - \boxed{\mathbf{K}_\mathrm{I}}\,[\mathbf{n}(k) - \boxed{\hat{\mathbf{n}}}]$$

- $\mathbf{u}(k)$: control vector of $u_{ij}(k), \forall i \in \mathcal{N}, j \in \mathcal{N}_i$
- $\mathbf{n}(k) \in \mathbb{R}^N$: state vector of region accumulations $n_i(k), \forall i \in \mathcal{N}$
- $\hat{\mathbf{n}} \in \mathbb{R}^N$: vector of the set points $\hat{n}_i$ for each region i
- $\mathbf{K}_\mathrm{P}, \mathbf{K}_\mathrm{I}$: proportional and integral gains.

(b) Data-driven online adaptation

- At each iteration, AFT algorithm receives
  - the measured performance index J (total delay of the system)
  - the measurable external disturbances $\mathbf{x}$ (aggregated demand)
- Using the samples of the measured quantities AFT calculates new tunable parameter values to be applied at the next iteration.



AFT: automatic fine tuning

Kouvelas, Saeedmanesh & Geroliminis, 2017

So let's invite the Tasios to discuss together how this algorithm works. Tasios please join us. Hello. So let's have a look on how AFT algorithm works. So AFT algorithm utilizes a learning technique which can be a polynomial approximate or a new work and tries to find the nonlinear mapping between these vector x with some which is some aggregated data from the network. These parameters theta that we need to optimize the tunable parameters and some performance index j which is the scholar in our case for example the total delay of the system so by collecting samples of data I can know this performance of the system j and I need to related to the data X and the parameters theta and the question now is which of the values of theta parameters which again correspond to KP KI and N vector and matrices. So which are the best values that can optimize the performance of my system j. So this is purely a data driven approach.

Notes

Summary

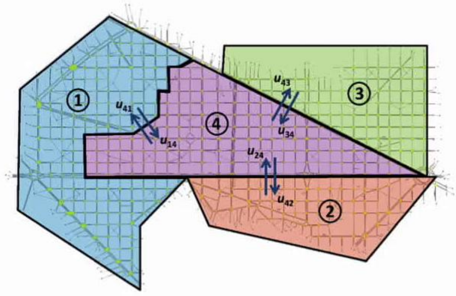
17m 28s

A more advanced controller (PI + parameter fine tuning)

(a) Model-based multivariable PI regulator

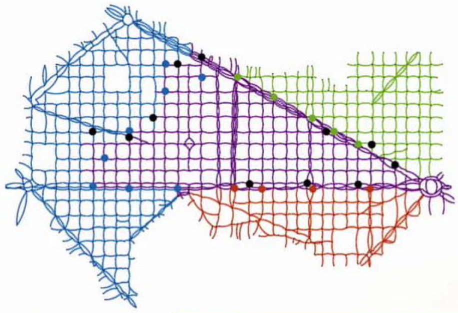
$$\mathbf{u}(k) = \mathbf{u}(k-1) - \boxed{\mathbf{K}_\mathrm{P}}\,[\mathbf{n}(k) - \mathbf{n}(k-1)] - \boxed{\mathbf{K}_\mathrm{I}}\left[\mathbf{n}(k) - \boxed{\hat{\mathbf{n}}}\right]$$

- $\mathbf{u}(k)$: control vector of $u_{ij}(k), \forall i \in \mathcal{N}, j \in \mathcal{N}_i$
- $\mathbf{n}(k) \in \mathbb{R}^N$: state vector of region accumulations $n_i(k), \forall i \in \mathcal{N}$
- $\hat{\mathbf{n}} \in \mathbb{R}^N$: vector of the set points $\hat{n}_i$ for each region i
- $\mathbf{K}_\mathrm{P}, \mathbf{K}_\mathrm{I}$: proportional and integral gains.



(b) Data-driven online adaptation

- At each iteration, AFT algorithm receives
  - the measured performance index J (total delay of the system)
  - the measurable external disturbances $\mathbf{x}$ (aggregated demand)
- Using the samples of the measured quantities AFT calculates new tunable parameter values to be applied at the next iteration.



AFT: automatic fine tuning

Kouvelas, Saeedmanesh & Geroliminis, 2017

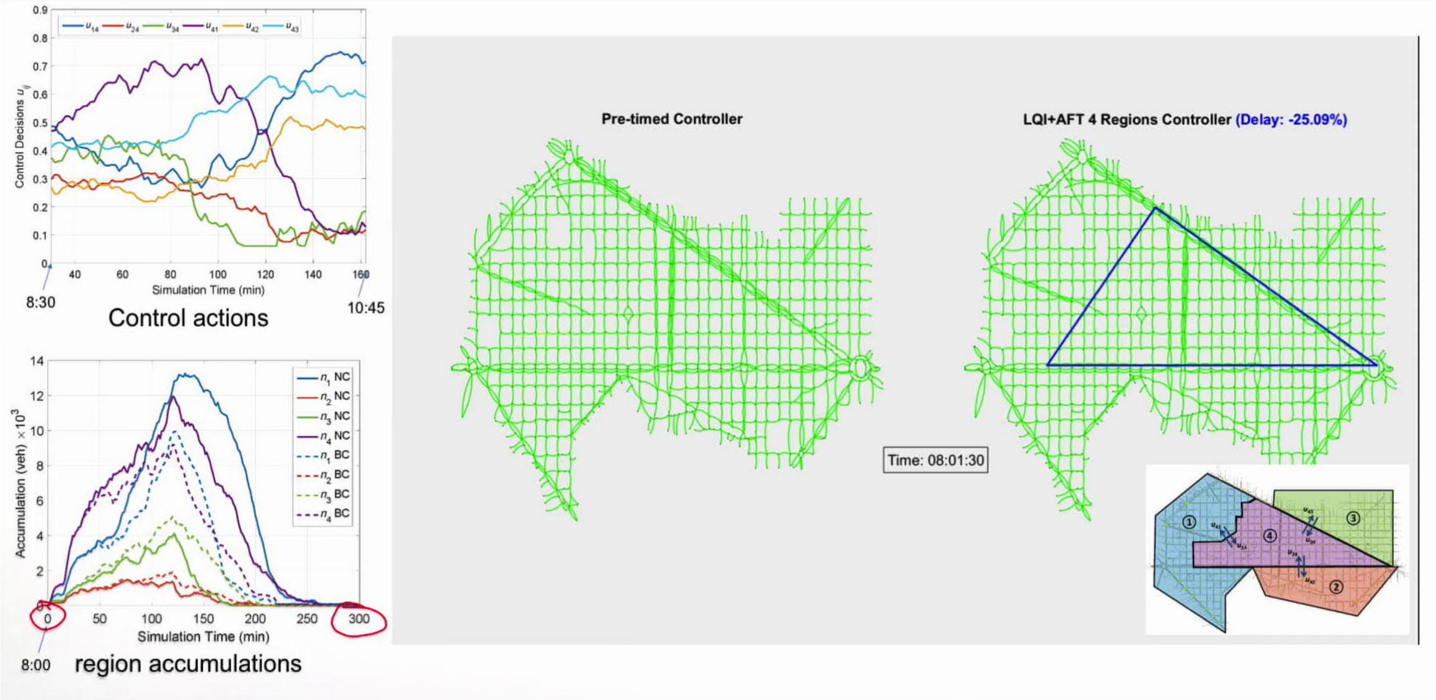
So let's see how we applied this algorithm in a micro simulation in a case study for the city of Barcelona there we see it in the figure of this slide. So, the city of Barcelona after the partitioning is divided in four regions. And what we have we have six control variables that are controlling the transfer flows between these regions. We have identified around 30 traffic lights that these traffic lights will change their green settings so that they meet their values of the variables that are estimated through the multi variable PI regulator after applying the AFT algorithm.

Notes

Summary

18m 46s

Micro-simulation results

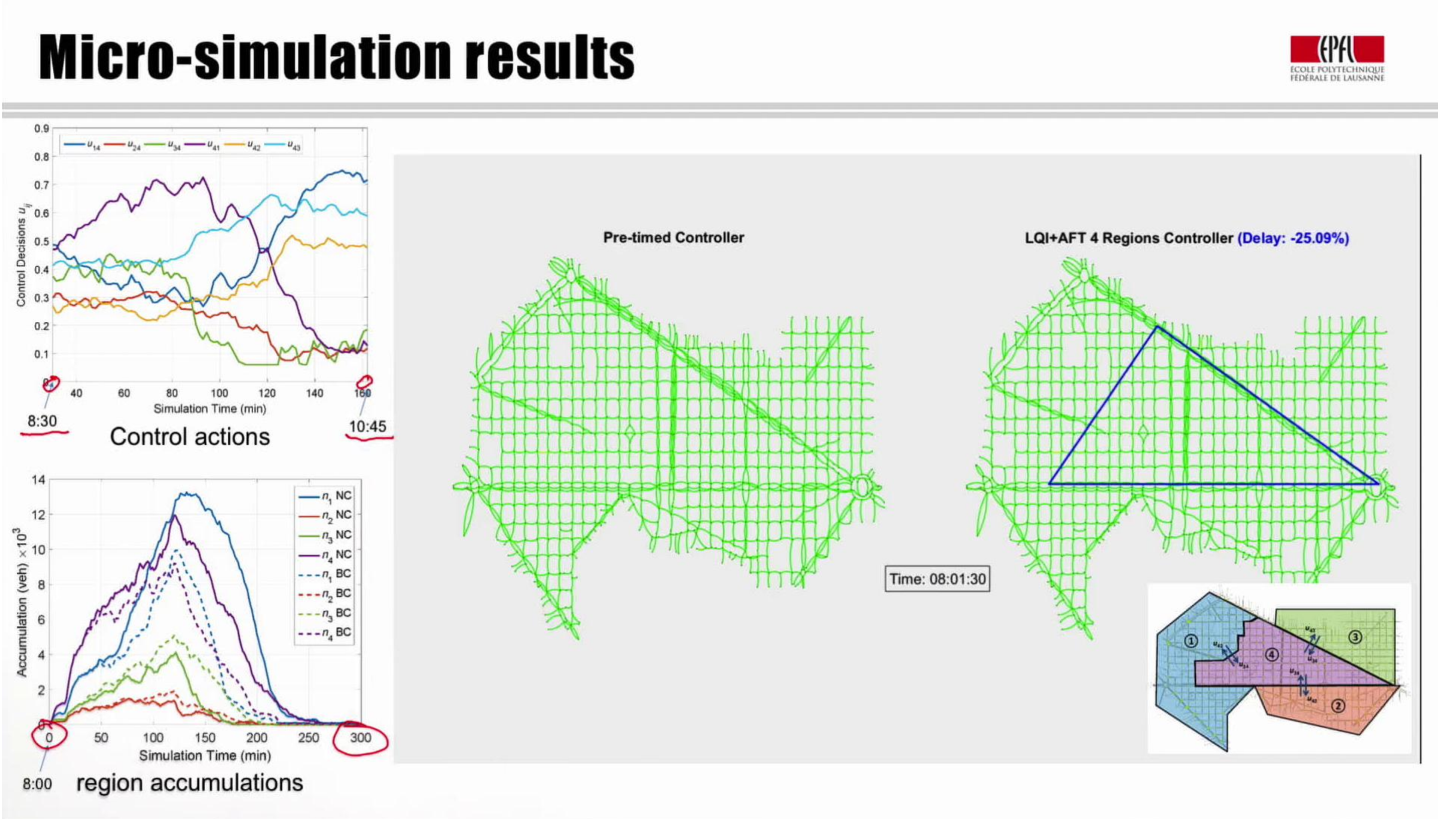


So let's see the application of these LQI plus AFT control algorithm in the micro simulation environment. So here we see two movies one with a pre time existing controller in the Barcelona network and one movie on the right with their LQI plus AFT. So what you could notice is that in the city center for example there are less red links which means are less congested. And actually what we also notice is that the network becomes uncongested much faster than in their pre time control case even if the same demand occurs in both situations. So we're able to serve the vehicles with less delays and arrive at their destination faster. So if we look at the two graphs the upper graph shows the control decisions for the six control variables with time. While the graph below shows the accumulation of each region without controlling the no control case and when we do boundary control BC. So I would like to ask Tasios to explain to us these control actions and interesting you note that control actions are only between 8:30 and 10:45 where our simulation is between 8:00 in the morning and 12:00. So note here that the duration of the simulation is five hours or 300 minutes.

Notes

Summary

19m 32s



However our controller is activated around 8:30 and deactivated around 10:45. The reason is that when we have light traffic conditions in the network there is no need to apply our controller so the pre time plan is sufficient for these conditions. So we define some thresholds for activation and deactivation of control in the simulation is from 8 to 12 o'clock and this is the activation and deactivation point. If we look now at the trajectories of the control inputs we can see for example 41 and 14. So, when the one increases the other decreases because they are antagonistic. The one is flow from region 1 to region 4 and the other flow from region 4 to region 1. So in that in the onset of congestion 4 1 is increasing and 1 4 is decreasing but in the offset of congested congestion it's the opposite. 4 1 is decreasing and 1 4 is increasing.

Notes

Summary

20m 59s

MFD control - Summary

We show together how to develop different type of perimeter control strategies for single and multiple regions. We will also investigate some different techniques which is known as Model predictive control where are utilized to optimize systems with non-linear dynamics. See you soon.

Notes

Summary

22m 05s