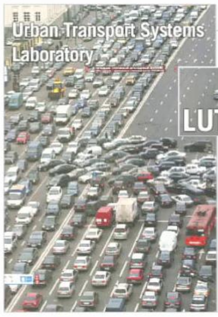
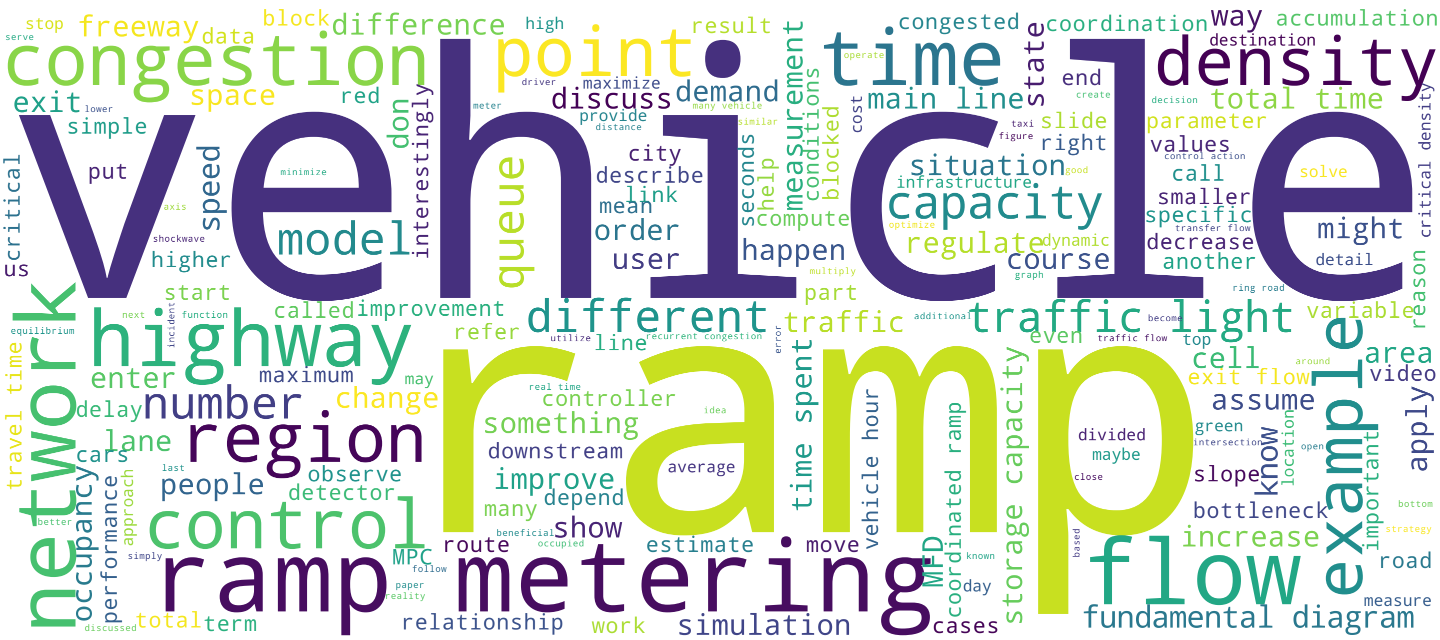
Applications – Ramp metering

Intro to traffic flow modeling and ITS

Dr. Anastasios Kouvelas





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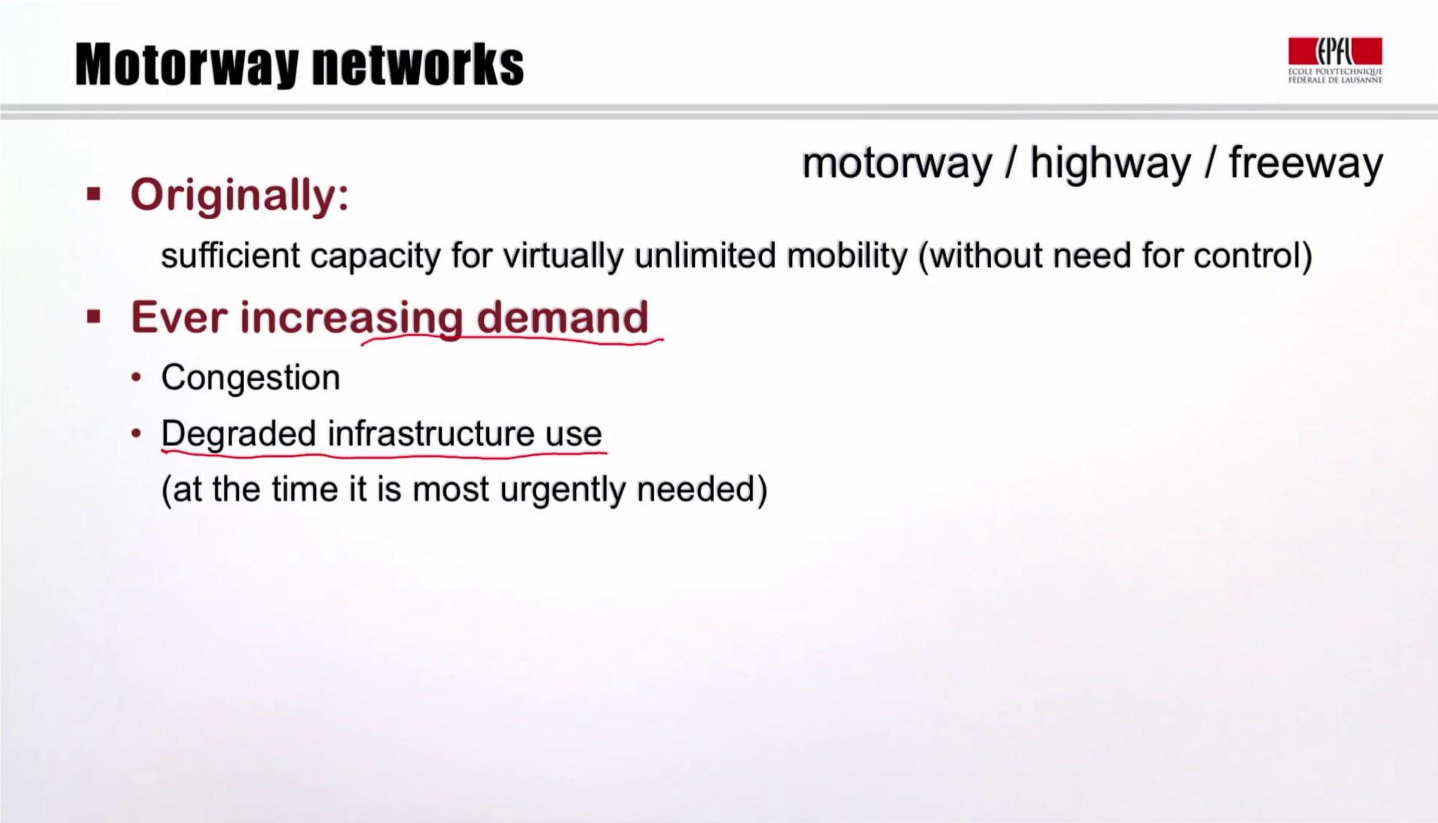


Hello, my name is Anastsios Kouvelas and in this video, we are going to discuss about ramp metering. Ramp metering is the most popular technique for managing congestion in highways. It refers to the use of traffic lights at the highways on the ramp in order to regulate the flow of vehicles that enter the highway. Nowadays, we have concrete evidence that with ramp metering, we can decrease traffic congestion in highways and improve driver safety. So, in this presentation, we are talking about motorway networks. I would like to point out that I am going to use the work motorway, highway or freeway referring to the same thing. Which is a road network that is closed, that doesn't have any intersections and you can enter through on-ramps and exit through off-ramps. When a motorway is originally constructed, it didn't have a lot of demands so people felt that motorways or highways are a way to deal with airborne congestion. Initially, we thought that we can have unlimited mobility and there can't be any congestion in such networks but this is not true. Because of the increasing demand, we do have a lot of congestion nowadays in our freeway networks and this causes the degradation of infrastructure.

Notes

Summary

0m 05s

Motorway networks

motorway / highway / freeway

- **Originally:**
  sufficient capacity for virtually unlimited mobility (without need for control)
- **Ever increasing demand**
  - Congestion
  - Degraded infrastructure use
    (at the time it is most urgently needed)
- **Congestion: recurrent and non-recurrent**
- **Control goal: Operate freeway networks optimally**
  (as a controllable system)

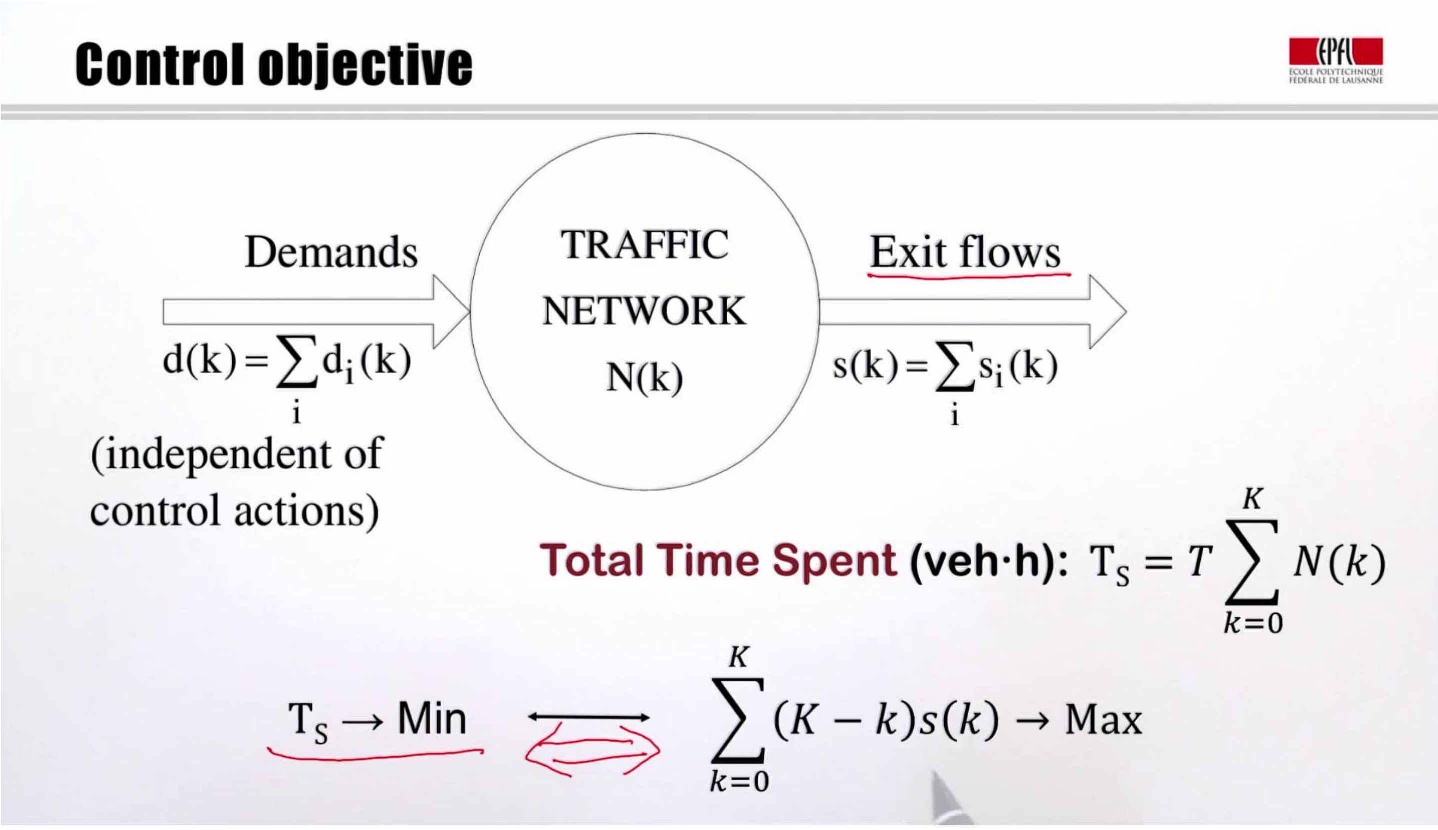
Ramp Metering: direct impact on density → congestion

So a motorway is designed to serve a number of vehicles per hour but this decreases because of congestion and propagation of queues. At the time that we need this capacity, we have reduced capacity because of congestion. So we can separate congestion to recurrent and non-recurrent. Recurrent congestion is something that happens almost every day. We know that if I go from my home to my work, there is a place that is an active bottleneck and this happens almost every day due to high demand and this is a recurrent congestion. But the non-recurrent congestion is something that can happen because of an incident, because of some accident or because of some special event. The control goals for our freeways is how to operate our freeways optimally. So we can see a freeway as the optimal system and try to optimize it’s performance. One of the control measures that we have for doing this is ramp metering that we are discussing today and I want to point out that ramp metering has a direct impact on the highway density so it can affect the congestion of the network.

Notes

Summary

1m 35s

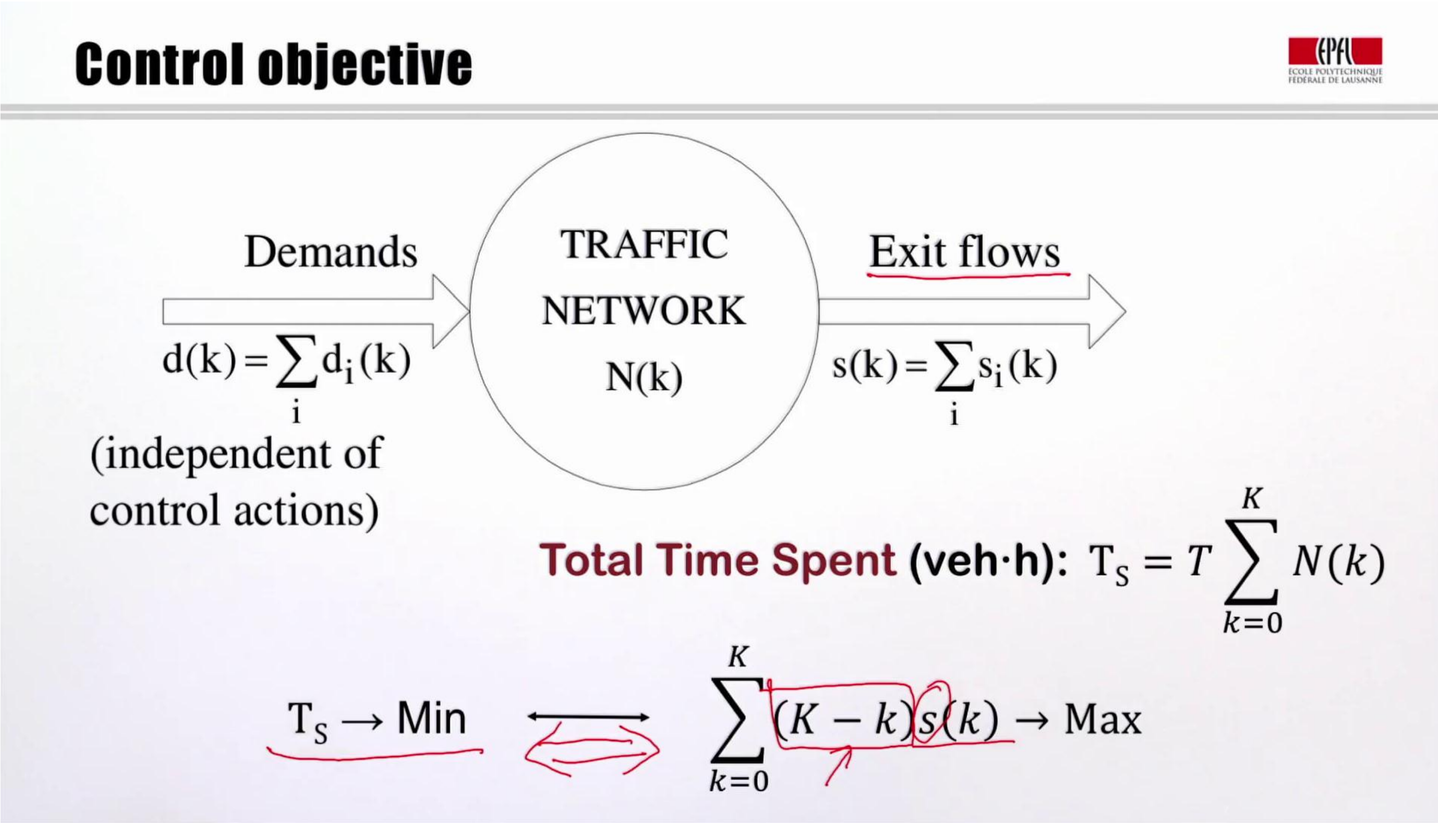


So let's discuss a bit more, the control objective. If we see our traffic network as a purely demand and supply system, we have some demands that we can assume are independent of our control actions. So I have some demands coming into the network and by doing some control action here, I can affect the exit flow of the network. So I have some exit flow defined here by S and if I don't see this as a demand supply system, my purpose is to improve the exit flow of the network to control it in such a way that I optimize the performance of the system. One measure that we have to access this is the total time spent, it is the vehicle hour travels by all the vehicles. If in this network, I have this N(k) which is the accumulation of all the vehicles, how many vehicles are in the network. If I sum this [k=0] overtime of the accumulations and I multiply with the time spent of the model. I take the total vehicle hours traveled and this is a criteria to access my control property. So my objective would be to minimize T s; the vehicle hours traveled. But someone could see this as another objective so it is equivalent more or less with maximizing the exit flow of this network.

Notes

Summary

2m 56s

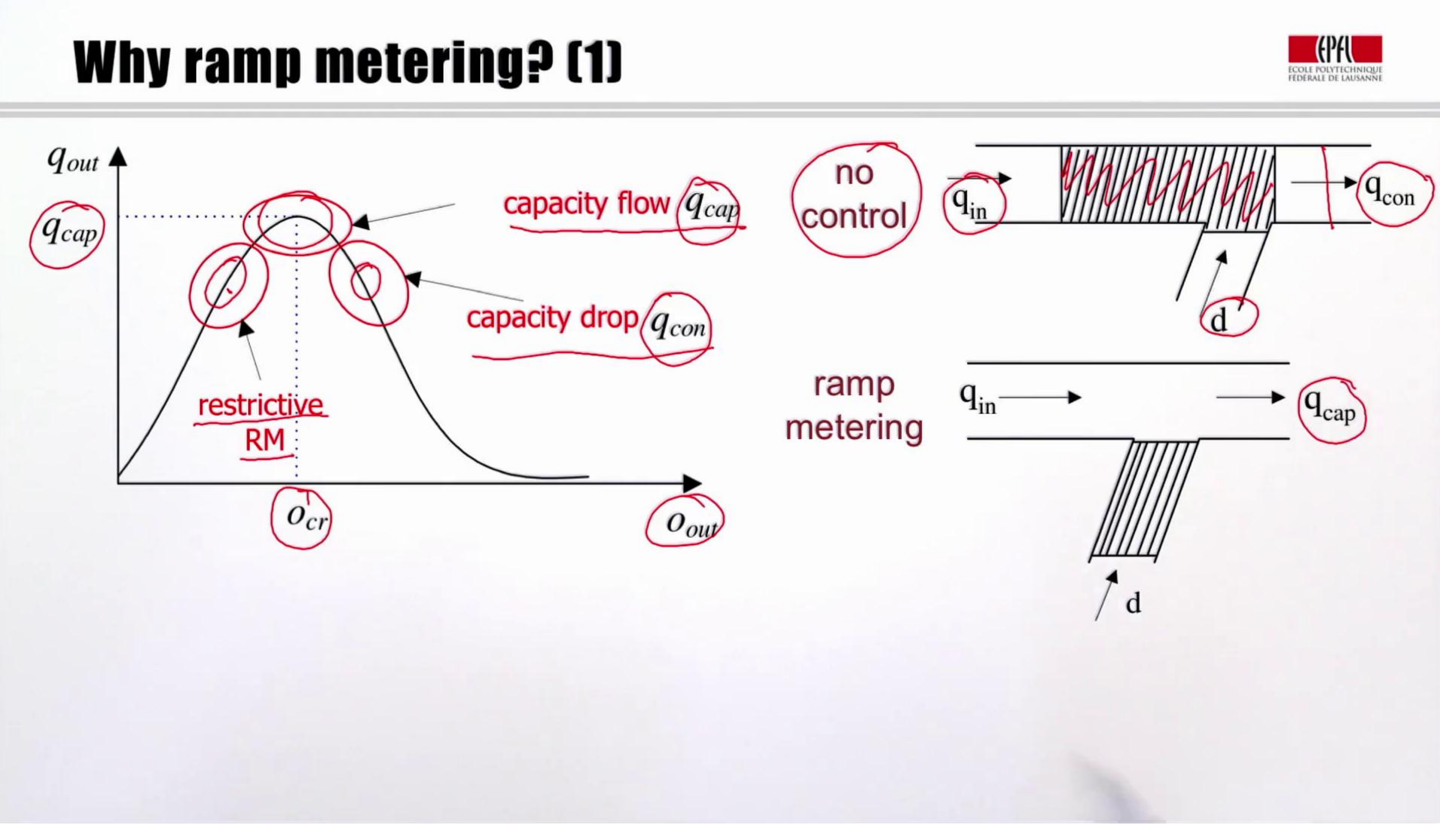


So if I try to maximize this S; the people that exit overtime, I have achieved again and minimized the total time spent. Of course, here, I need to multiply with this factor, which is a time index, which says that I have to exit the vehicles from the network as fast as possible.

Notes

Summary

4m 33s

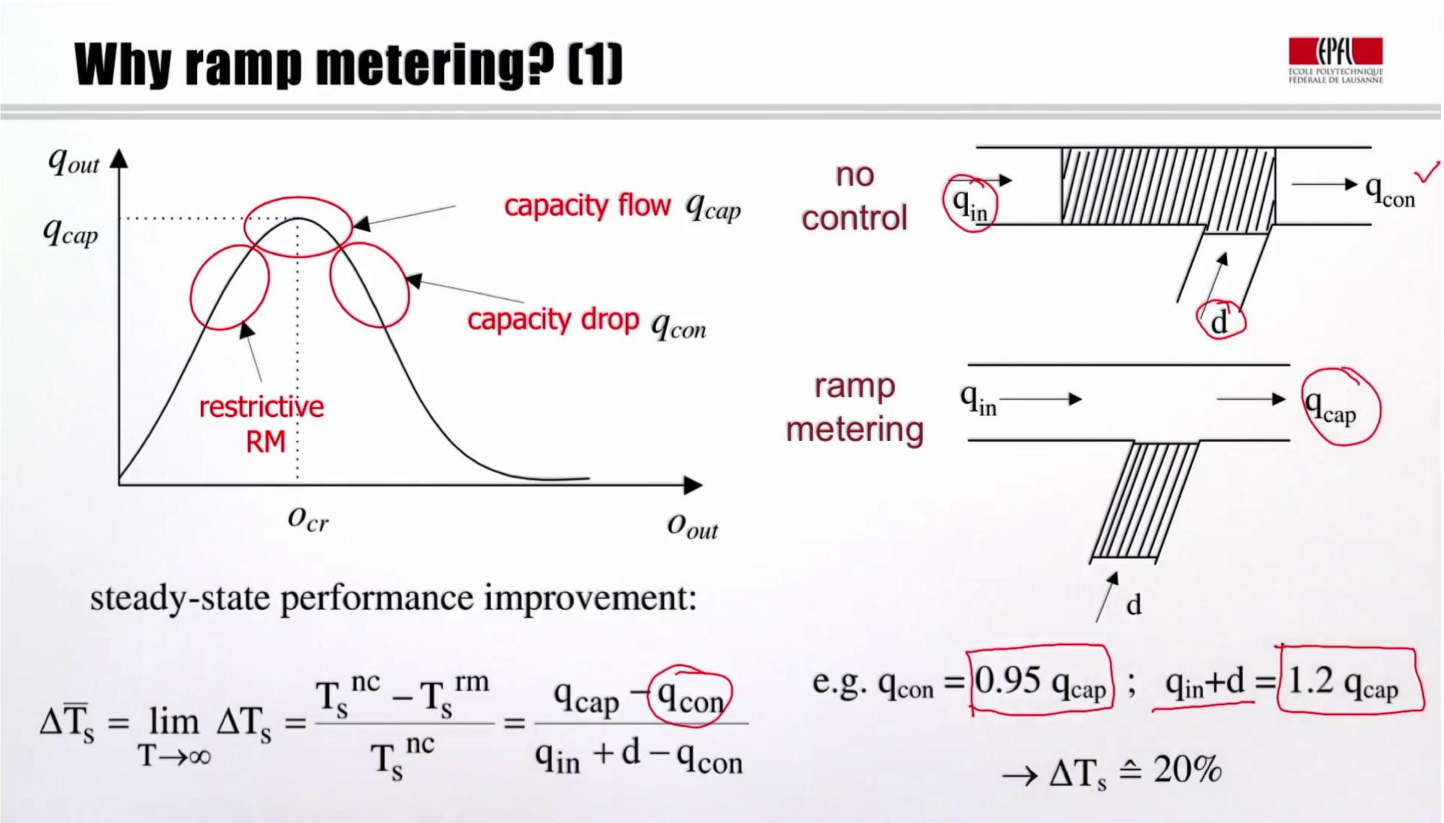


Let me now give you some examples of why ramp metering works. First of all, I am going to utilize the fundamental diagram of traffic engineering. So we have this relationship between density and flow and we have some maximum flow here, which is the capacity of my cell or my network. What I can observes in reality is something like this area here, which is smaller than the capacity flow and I call this the capacity drop. This is a flow Q congestion, this is Q capacity and of course, I can also be in this area where I don't have enough density, I am below the critical density. One example of this is if I do restrictive ramp metering. If I hold vehicles back in the ramps, I underutilize my infrastructure and I have less flow. Let us go to the right for one example. The first case is if I do no control so the ramp is open and everyone can go in and because of excess demand, I have this demand here and some in flow here in the main line. So if I sum this two, I have some total demand and this creates some congestion in the main line. Because of this congestion, because of this bottleneck, I can move here, the outflow of this small area and I would eject some flow that I call q con and this can be smaller than q capacity.

Notes

Summary

4m 58s

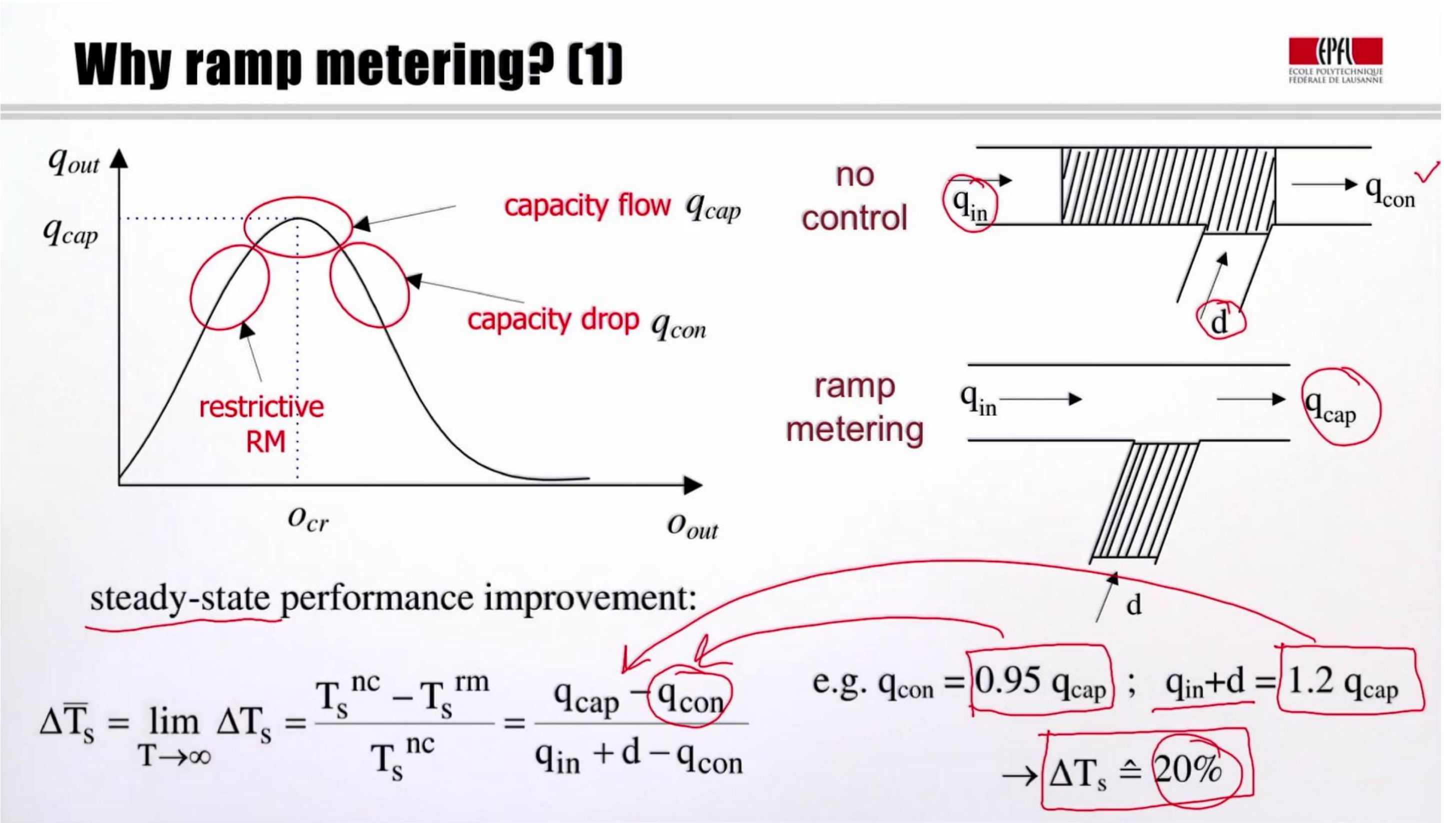


I refer again here and here. So the other option is to do some ramp metering, I hold some vehicles on the ramp with traffic lights. I stop them here, they have to wait for some time but then, they do not block the main line of the freeway. Then I can increase the capacity of this point if I get measurements. So this is one reason why ramp metering can improve the situation and I would give you some numerical example. So in this case, if I want to calculate the difference of the total time spent for a long time, I assume here that I have a steady state conditions. So I can compute the total time spent for the no control case, the total time spent when I do ramp metering and find this improvement. It is easy to show that the difference is the capacity flow minus the congestion flow. If I put in the denominator, the total time spent for the no control case, I can find the improvement. Let me give you some numbers here; if I assume that the congested flow is the 95% of the capacity, so I have a 5% decrease here because of the bottleneck. If I assume that my total demand; this demand plus the total flow of the main line is let’s say 1.2 times this flow capacity.

Notes

Summary

6m 48s

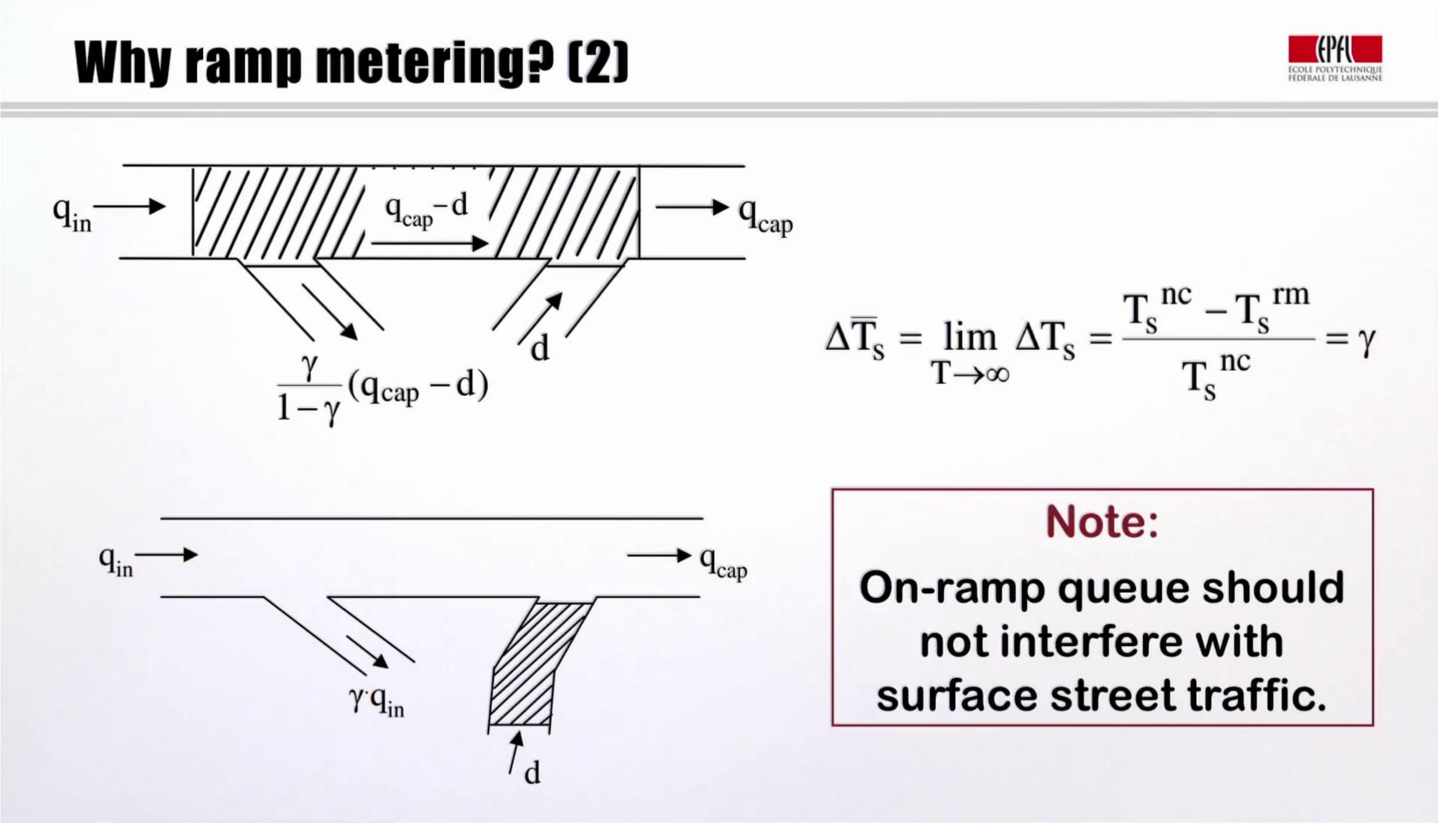


It is 1.2 times higher than the capacity of this area and if I replace this 2 here and do some calculations. It is very easy to show that I have a difference in the total time spent of 20%. By controlling the ramp with this simple numerical example, which again refers to the steady state. I can easily calculate that I can have a 20% improvement in the total time spent.

Notes

Summary

8m 34s

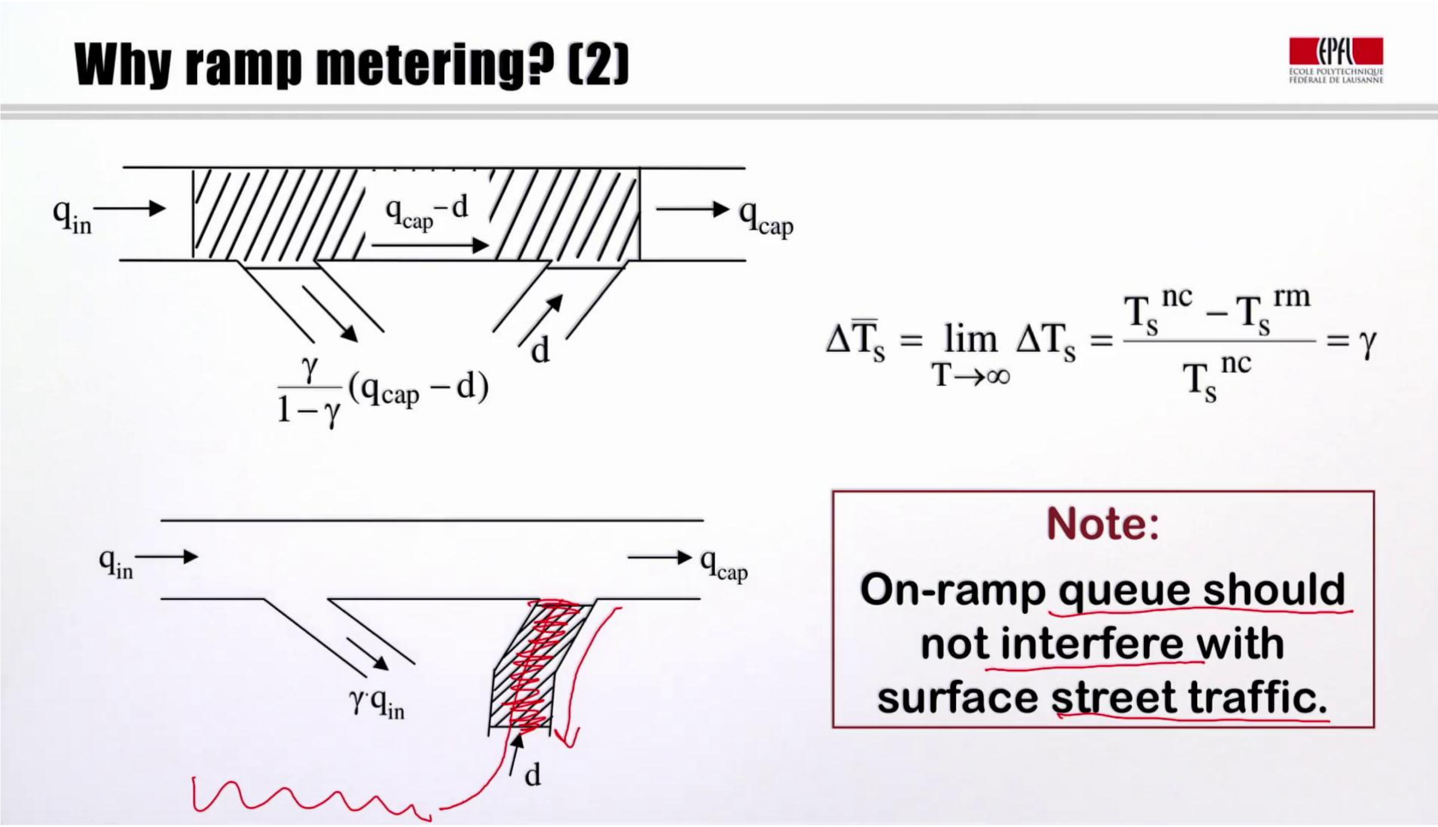


I would like now to demonstrate with another example why ramp metering can be beneficial for a highway. So I have again on the top, the no-control case where I don't do anything on the ramp. I have this on the ramp and I have this off-ramp and I have some demand here and some flow here. Let's assume that I have this flow capacity here and I have some congestion because of excess demand. If I do ramp metering in this case, I can get some improvement because this off-ramp is no blocked. So I can hold some vehicles here and clear the congestion here in the main line. I don't block the off-ramp so there are people here waiting in the queue that want to exit from this off-ramp but because this off-ramp is blocked, they cannot exit. In the second case, these people can exit from the off-ramp. Again, if I put some simple numbers here, so I put this ɤ, which is the split ratio of the percent of people that want to exit. So from all these people here, ɤ% want to leave the freeway so now, they can exit because the off-ramp is not blocked. If I compute again the difference between the no control and the ramp metering policy, I get this ɤ as a percentage for improvement for the total time spent.

Notes

Summary

9m 10s

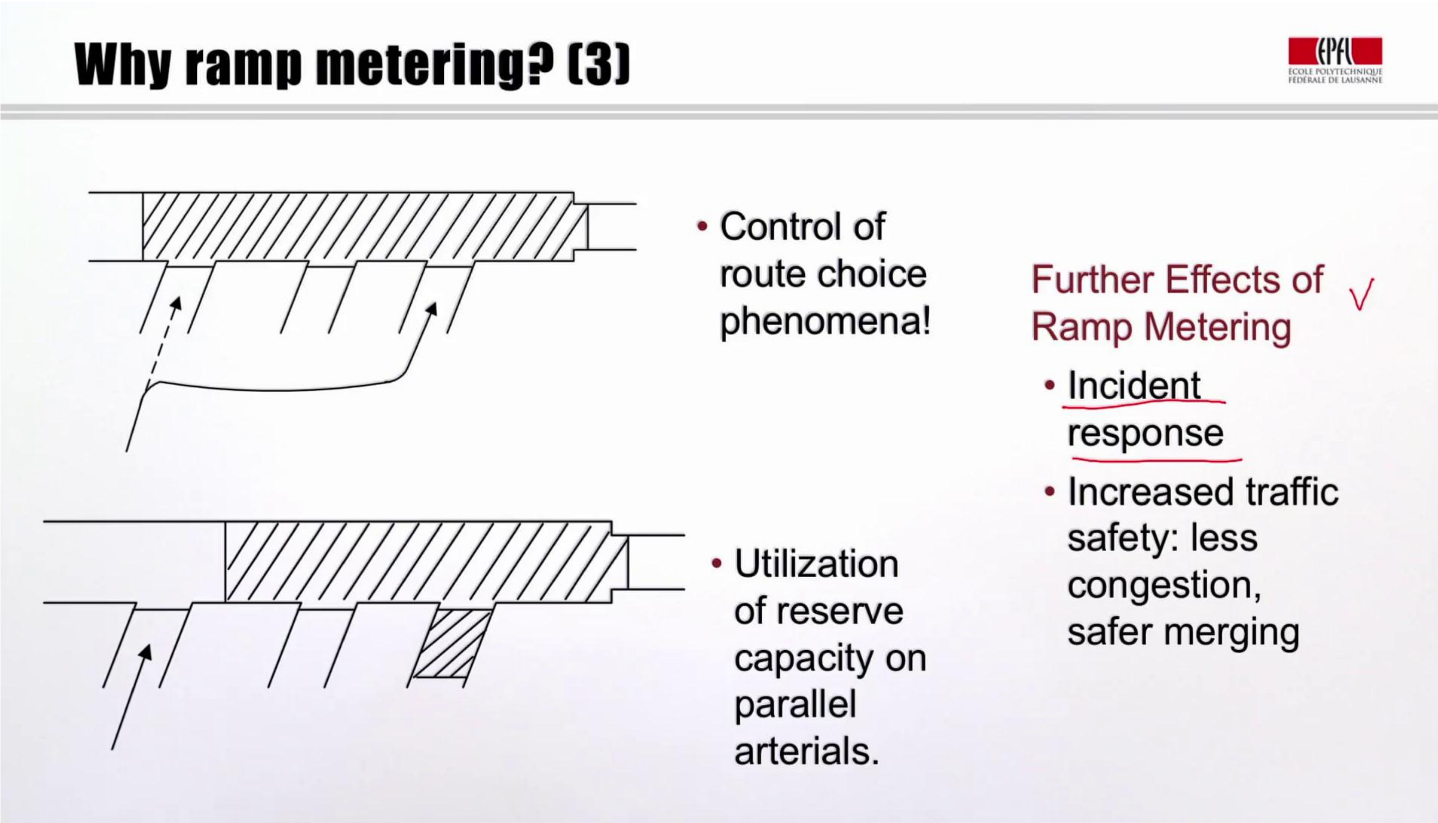


One key issue here that I would like to note is that I can control this on tamp and I can have some queue of vehicles here. But a basic argument here is that this queue here should not block the neighboring arterials. As long as this queue doesn't interfere with the street traffic that is nearby, I don't have any problem. But if this queue grows, then I would start getting problems and congestion in the rest of the network. So this is an important issue in ramp metering. This on-ramp has some storage capacity, I can store some vehicles but then I would start getting son troubles in the neighboring arterials.

Notes

Summary

10m 45s

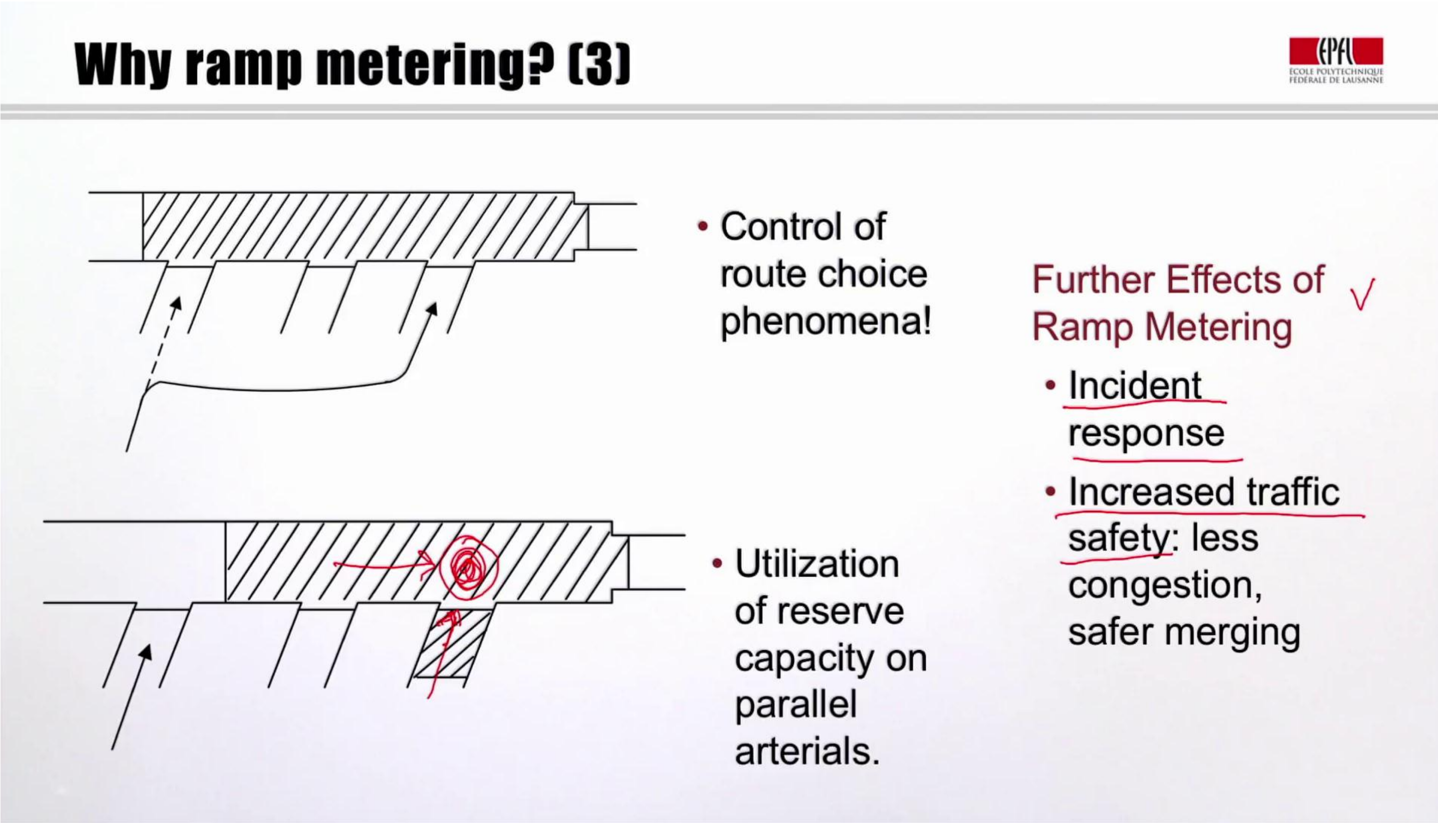


I have a very good example here that demonstrates why ramp metering can be beneficial. Again, on the top, we have the no control case so there is no control in the ramp and I get some congestion here that blocks another on-ramp. At the bottom, I can do ramp metering here and have a queue here so I clear this queue and this on-ramp is no blocked anymore. So people that want to enter from this on-ramp, they can enter but in the first case, this on-ramp is blocked and some people may decide to deviate, change the route and go to another on-ramp. So through ramp metering, I can control some route choice phenomena. People, when they try to enter a highway and they see congestion, they may try to change their mind and enter from an on-ramp downstream. This can also help me in the utilization of the capacity of the parallel arterials. So I have traffic from arterials that want to go to the highway and by having some excess capacity here, I can utilize better this traffic. There are other positive effects of ramp metering. One could be incident response so if I have an incident, accident or a special event, I can turn on-ramp metering on my on-ramp and try to deal with this incident.

Notes

Summary

11m 33s

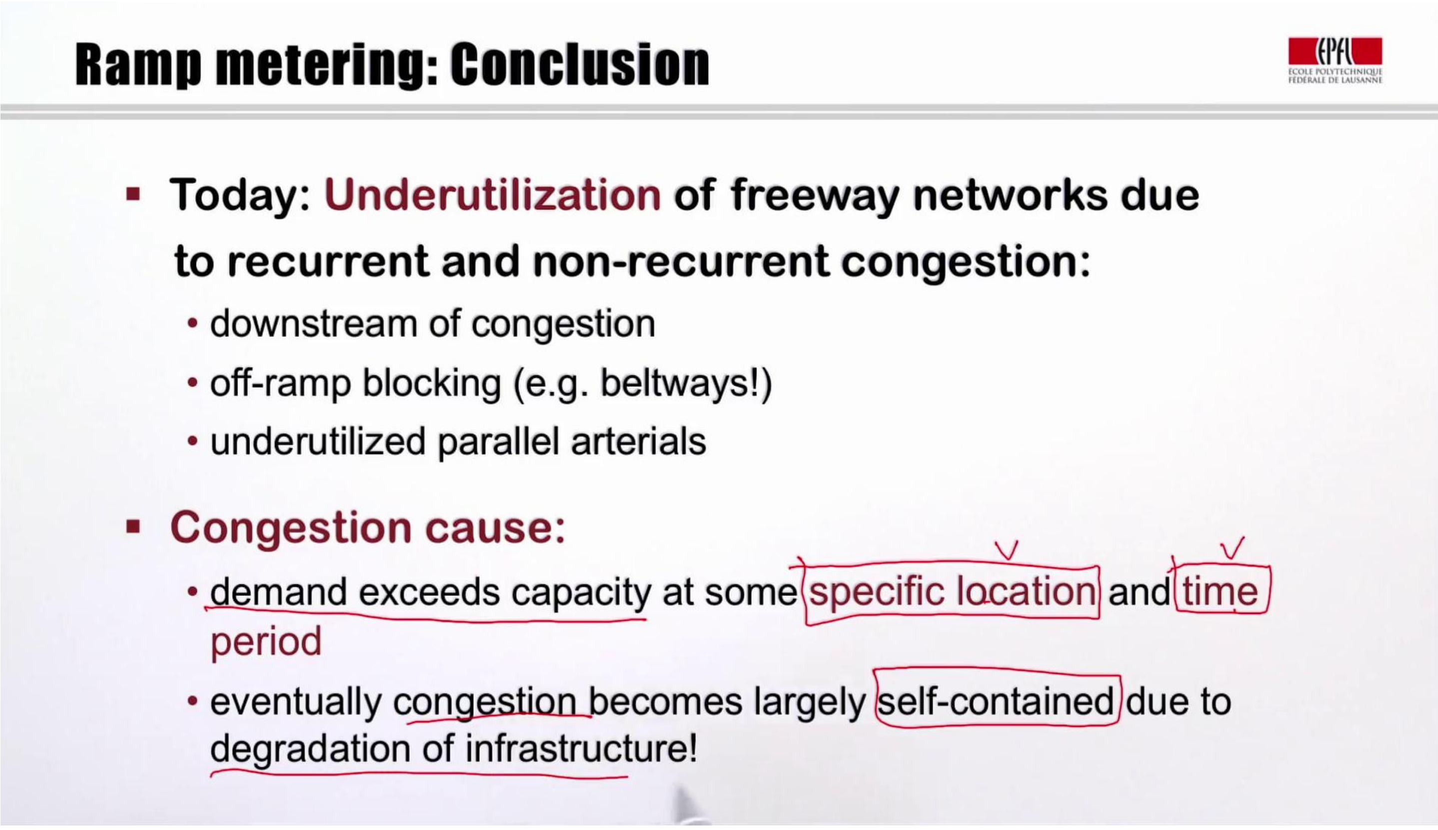


Of course, it is true that ramp metering increases traffic safety. So this is a merging area where the on-ramp merges with the main line. So if I regulate traffic here, this merge is safer. We have proofs for this and this increases the safety because too many accidents happen in this area because of the merging of the vehicles. We have too many accidents and this can be much smoother when I do ramp metering.

Notes

Summary

13m 05s

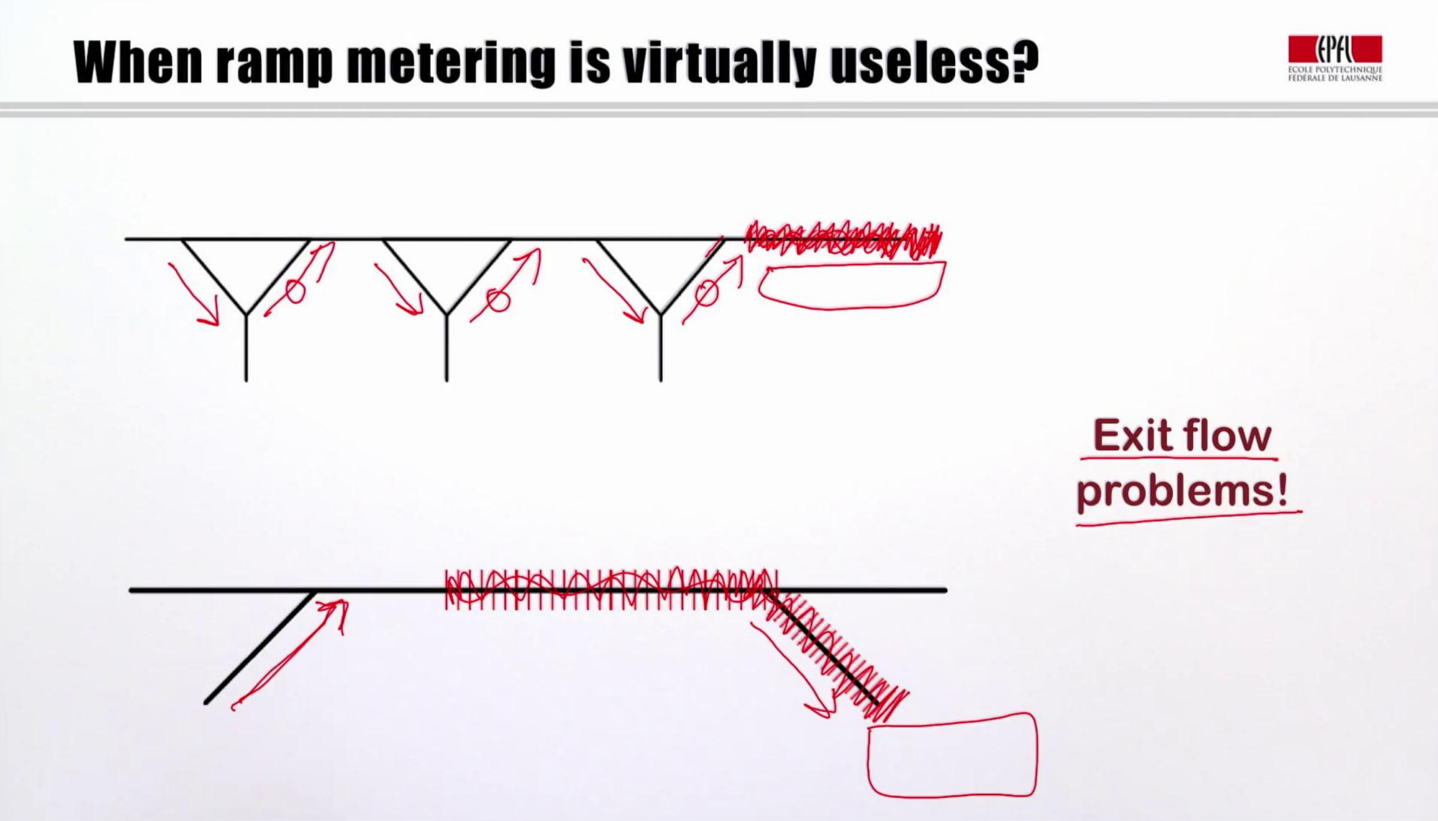


Let me in this slide some up the positive aspects of ramp metering. Nowadays, we know that we have underutilization of our freeway networks and this is due to recurrent and non-recurrent congestion as we discussed earlier. So we have underutilization downstream of congestion because of some bottlenecks downstream, we have empty highways and we have off-ramp blocking. We have ring roads or beltways that are blocked around the cities. Of course, another effect is that we have underutilized traffic flows in the parallel arterials. The basic cause for this congestion is that demand exceeds capacity but this happens only for some specific places and maybe a very small amount of time. If this happens at some place and for some time, this can propagate back and create confusion and block my system. One way to do this is to do control at this place and this specific time and try to avoid this or try to delay this congestion. Because if I let congestion spread, we know that this would propagate in my network and then congestion becomes self-contained. Then, we have the degradation of our infrastructure.

Notes

Summary

13m 41s



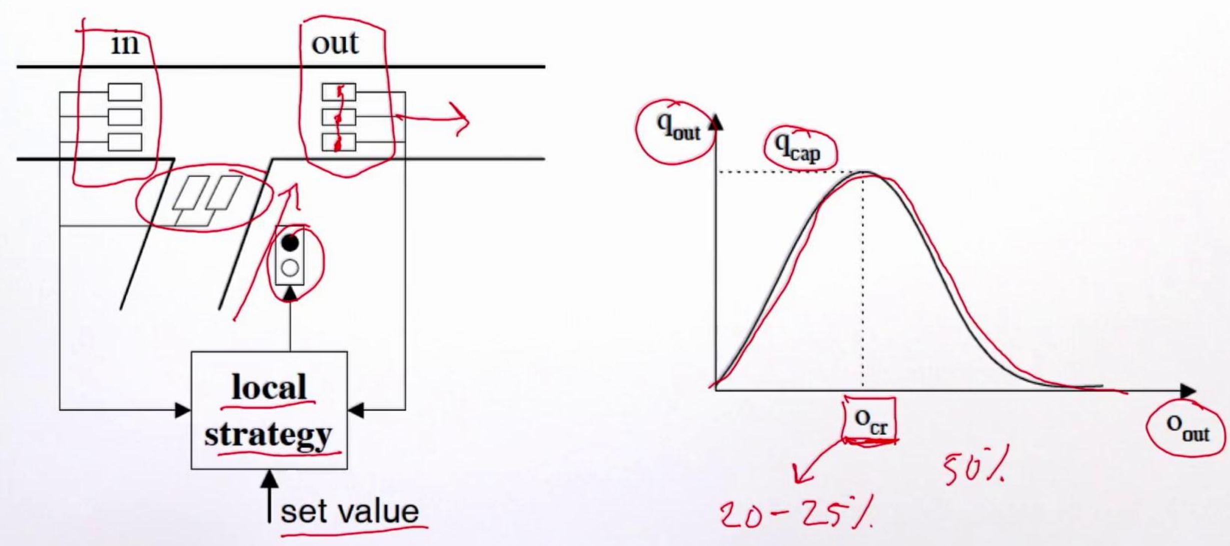
Now, in this slide, I provide a couple of examples but ramp metering is useless. But there are some cases where ramp metering cannot help me improve the situation on the highways. In some of these cases, for example, on the top picture of the highway, these are on-ramps and these are off-ramps. So if I have a situation like this where I have congestion here downstream for some reason. If I do ramp metering in these three ramps, it doesn't really help my problem. So even if I apply ramp metering and I regulate the flow, I cannot improve the situation because the problem is somewhere further downstream and the reason of this congestion maybe something else; maybe an incident. So I could do something in this area but doing ramp metering here cannot help the situation and it is obvious. Another example at the bottom is again when I have the blocked off-ramp. This is an off-ramp, this is an on- ramp. If for some reason I have a congestion that is created here because of the arterial downstream of something else and this propagates in the main line of the highway. If I go to this on- ramp and apply ramp metering again, I cannot improve the situation, I have to do something else for this problem here. Ramp metering in these two cases is not really helpful so when I have exit flow problems, ramp metering cannot really help.

Notes

Summary

15m 14s

Local ramp metering



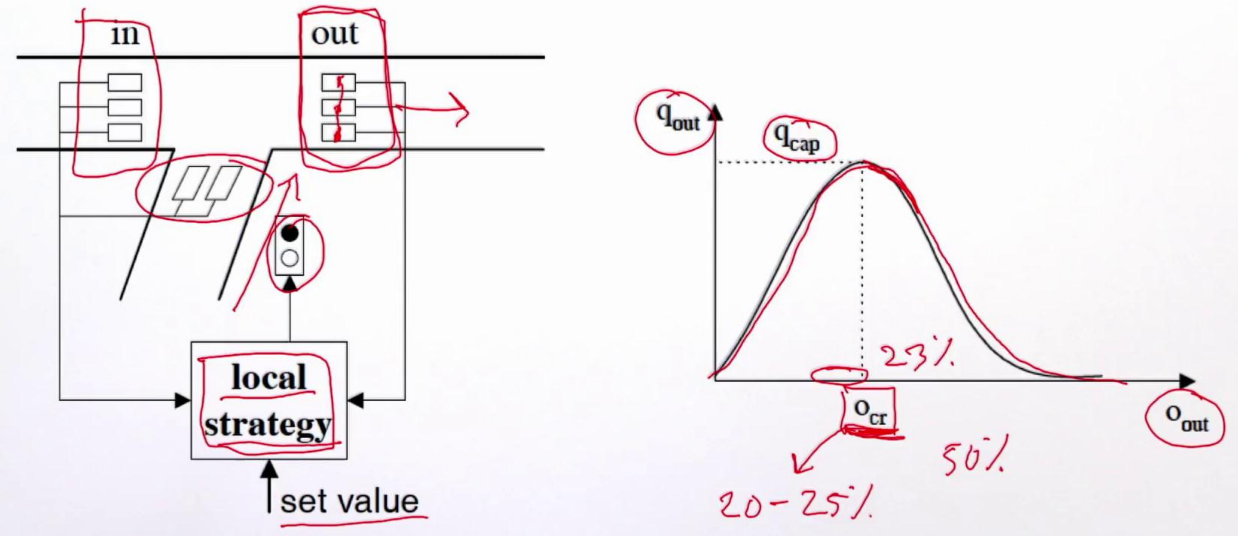
Let us not look at ramp metering strategies. First of all, we are going to discuss local ramp metering. So if I have one ramp here, the idea is that if I get measurements from this point and this point and also measurement from the queue in the ramp. I can derive a local control strategy here and apply it to the traffic light and try to improve the situation by some regulation. For example, I can use some set value for my controller and try to regulate this optimally. One important tool that we utilize is the fundamental diagram so it is this relationship of density and flow. So in this slide, I use this O, which is occupancy and it is time occupancy. So it is the percentage of time that these detectors here are occupied for example. If I count for 1 minute and 3 seconds and these detectors are occupied and 3 seconds, they are not occupied. This occupancy is 50%, it is a number from 0-100. This fundamental diagram gives me this relationship between flow and density or occupancy, which is a flow of density. We know that we have some critical value here that maximizes the flow here. Typically, to give you some practical examples, this critical value can be something between 20-25% for example.

Notes

Summary

16m 54s

Local ramp metering

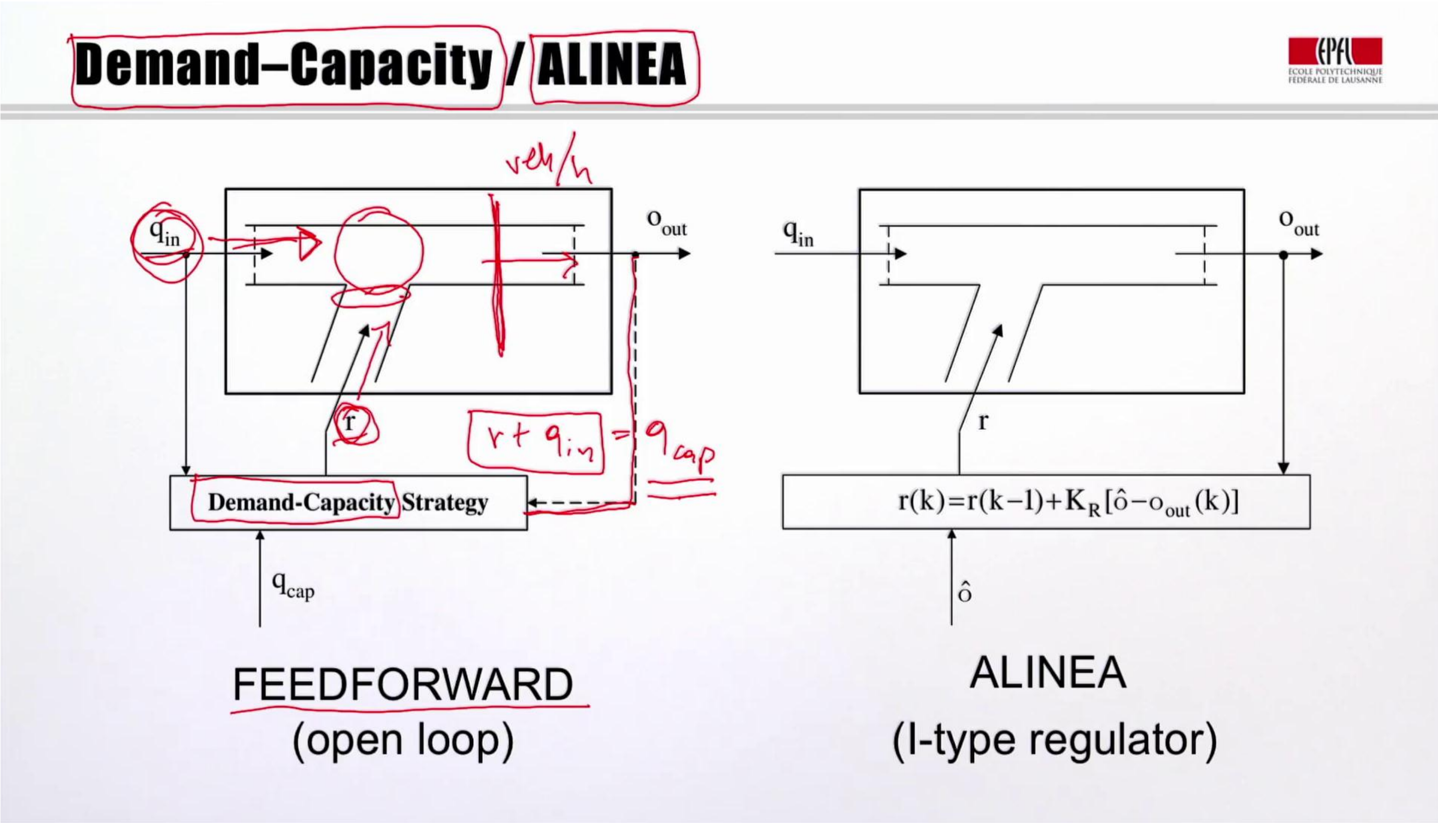


But this depends on the case, the network, the country and different aspects. So a good value can be 23% for example but it can also go down or up depending on the driving behavior and many other factors. So my purpose here is for this controller to try and regulate this density close to this number or a little bit lower than this number. So I make sure that I don't enter this congested region of the fundamental diagram and this is the idea behind ramp metering.

Notes

Summary

18m 44s

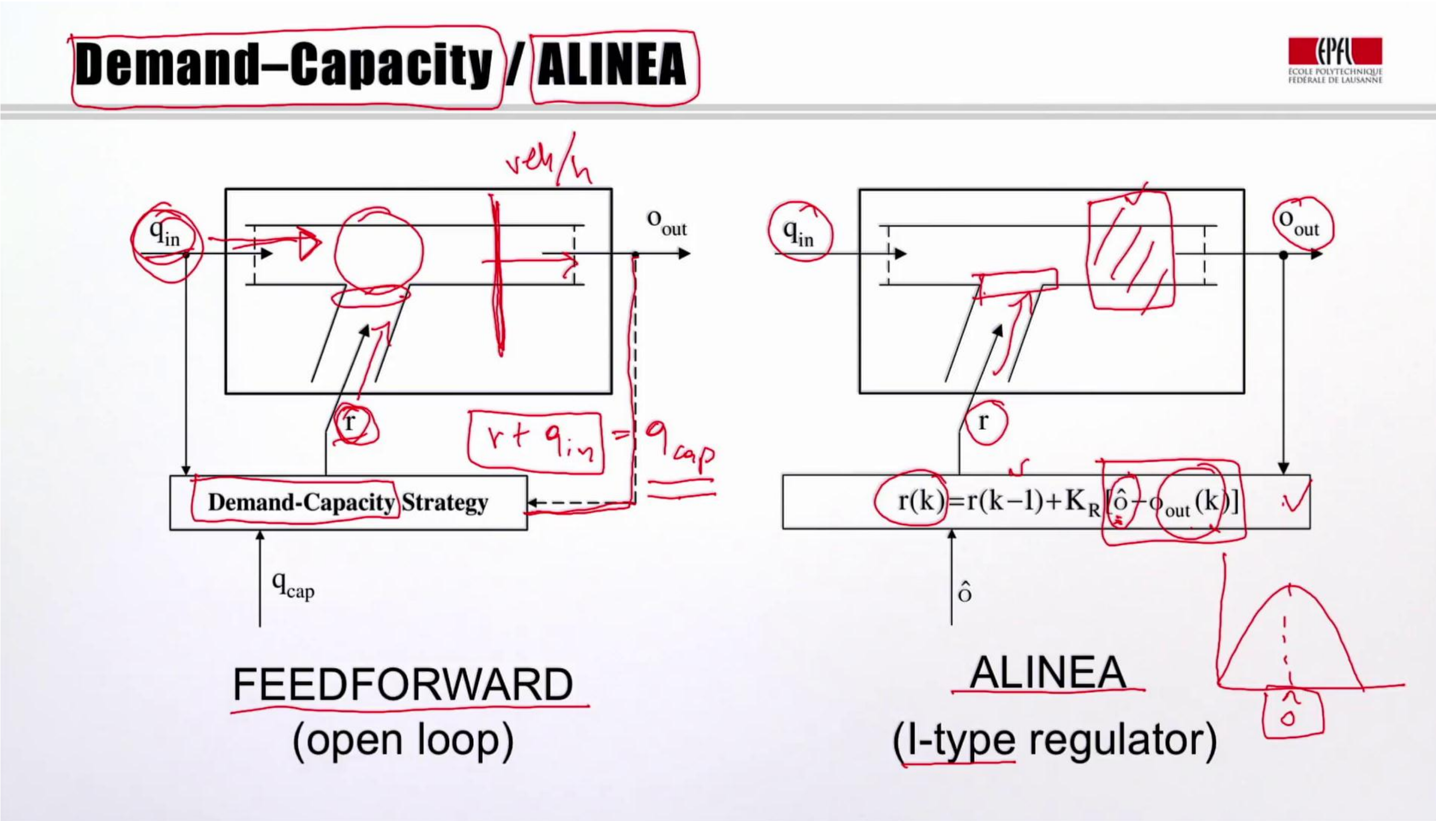


This slide presents the two most well known local strategy for ramp metering. One is called the demand-capacity strategy and the second one is ALINEA. So let me discuss the first one, if I have this ramp here and if I know this demand that I have in the main line, qin and I know the capacity of this point; how many vehicles per hour I can serve here, what is the maximum capacity. Then I can regulate the in flow from the ramp (r). But the summation of r+qin is equal to the capacity of this point. So I can regulate with the traffic light here and make sure that this summation doesn't exceed the capacity of this downstream area. So this is the merging area where the ramp merges with the main line and this is the area downstream of the merging area. So this is called demand capacity strategy because I know my demand and I know my capacity and I can regulate the traffic light so I make this two equal. Let me point out that this is a feedforward approach, it is open loop. I don't have any feedback here, this part is open, I don't get feedback from this downstream location. I only regulate qin, I have r and I have a fixed value that I want the summation to be lower than or equal to this fixed value.

Notes

Summary

19m 26s

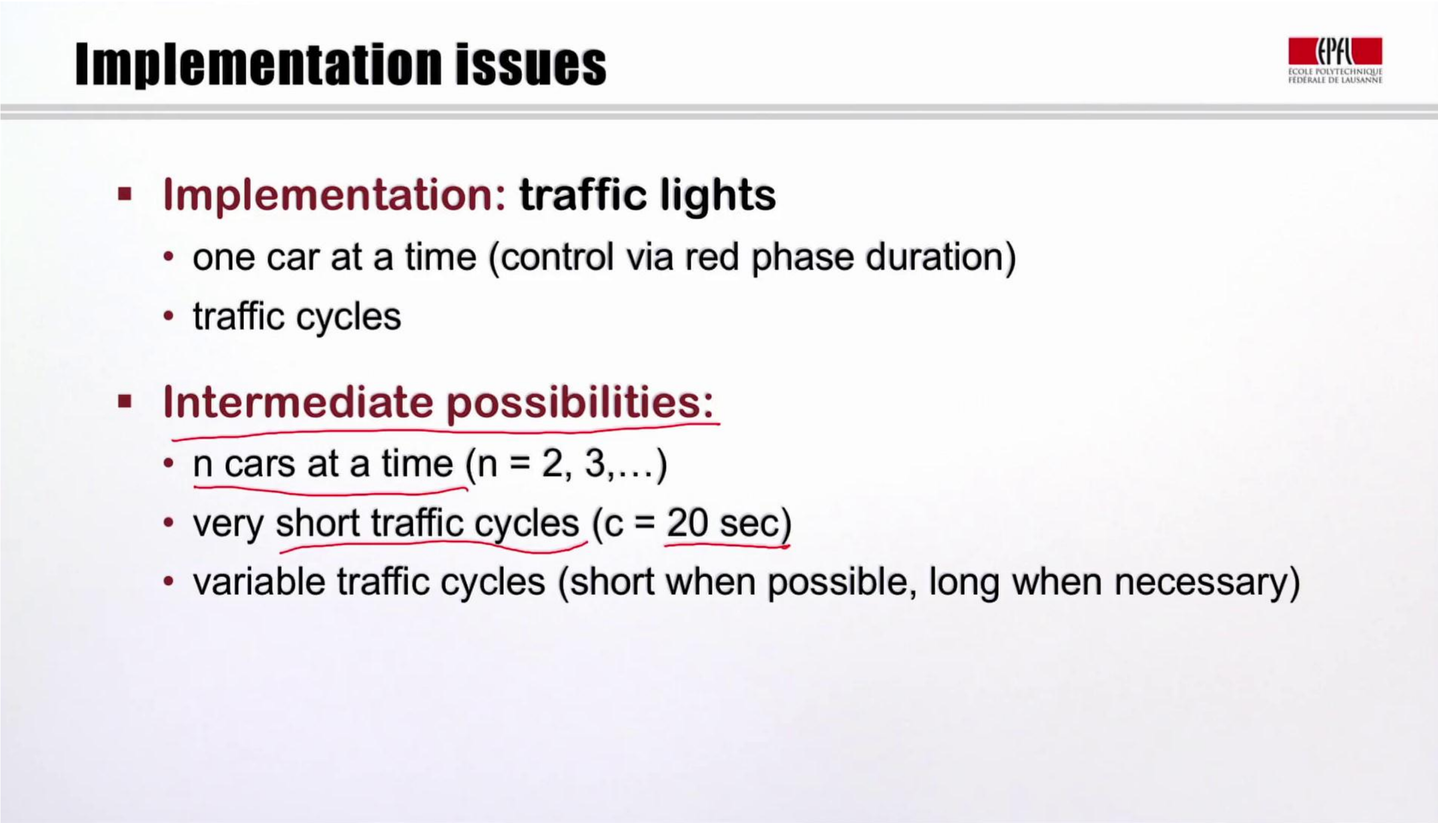


The second approach is quite similar and it is called the ALINEA. This is an I-type feedback regulator and here is the equation that gives this ALINEA regulator. Again, I have some in flow in the main line, I have some flow that wants to enter the highway from the ramp and I put here some traffic light that meter the in flow. Giving some fundamental diagram for this area, here, I can know the capacity of this area. What is the optimal point to regulate the density in this area. So this regulator just does this. So I have this O^ which is the critical occupancy and I have the measurement at this point that measure the occupancy at this point. Depending on the difference between the first point, which is my critical density and the actual measurement of the density. I can increase or decrease the incoming flow on the ramp. So this is the flow that I would allow of vehicles per hour to enter the ramp and this is equal to the previous step plus some difference that depends on this difference of critical density and my measurements.

Notes

Summary

21m 16s



So let us now discuss the implementation issues of ramp metering. I have a strategy that defines the flow that I should allow from the ramp to enter the highway in vehicles per hour. How can I apply this to my traffic lights, which are my actual [inaudible 23:15]. There are different ways to do it; one is the popular approach in the US, which is what we call one car at a time approach. So I can have a flashing traffic light flashing green and every time I have a green time, only one car is allowed to pass. The next one has to stop and wait for it to flash green and pass. This is called on car at a time and it is something very poplar that they do in the US to regulate and homogenize the in flow of the traffic. But I can also apply this with a traffic cycle. So I can have in my traffic light the cycle and some red duration and some green duration. In that case, during the green, I have in flow and during the red, no one gets in. of course, there are other approaches, intermediate impossibilities. So I can have n cars at a time when n is 2, 3, 4 or whatever. Usually, in the traffic lights of ramps we use short traffic cycles, something like 20 seconds.

Notes

Summary

23m 00s

Implementation issues

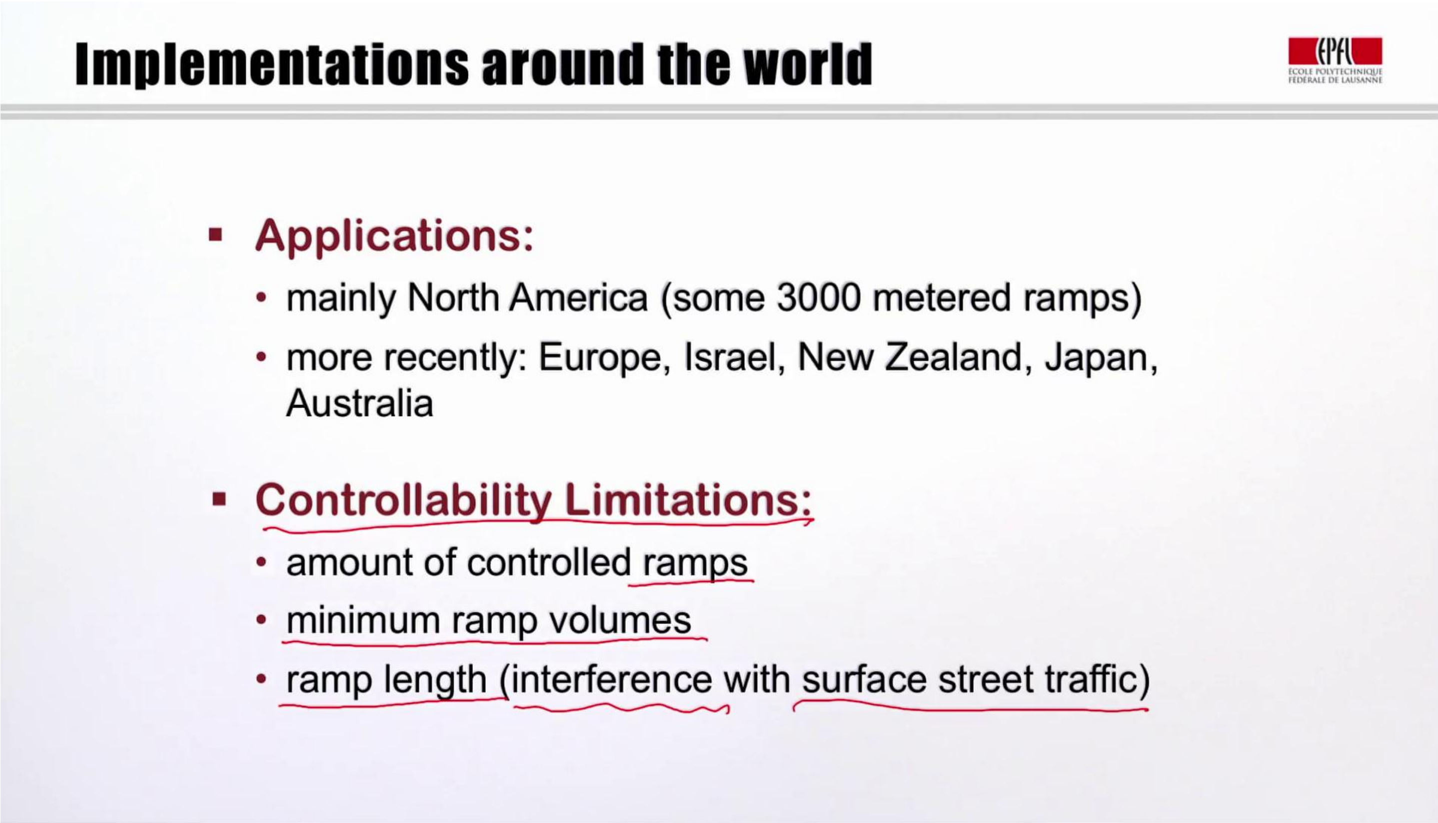
- **Implementation: traffic lights**
  - one car at a time (control via red phase duration)
  - traffic cycles
- **Intermediate possibilities:**
  - n cars at a time (n = 2, 3,…)
  - very short traffic cycles (c = 20 sec)
  - variable traffic cycles (short when possible, long when necessary)
- **Ramp capacity: Important for efficiency**
  (skip the red phase!)

But we can also use variable traffic cycles so it can be short, long or whatever you want. This is the way to apply the flow that you get from your regulator to the on- ramp. A key aspect here is the ramp capacity so it is very important for my ramp strategy. Every ramp has a storage capacity in vehicles and after this, if I reach this capacity, I don't have any other option, I have to open the ramp, I have to skip the red phase and everyone gets in the highway because it is blocked and I would have problems in the arterial. So imagine the highway with on-ramps that have infinite storage capacity. In this case, I can solve the control problem exactly. So I can store as many vehicles as I want to the ramp because of it's infinite storage capacity and I can make sure that the main line of my highway is always free flowing, there is no congestion. But because this is not the case and we have some physical storage capacity, the problem becomes more complicated.

Notes

Summary

24m 29s

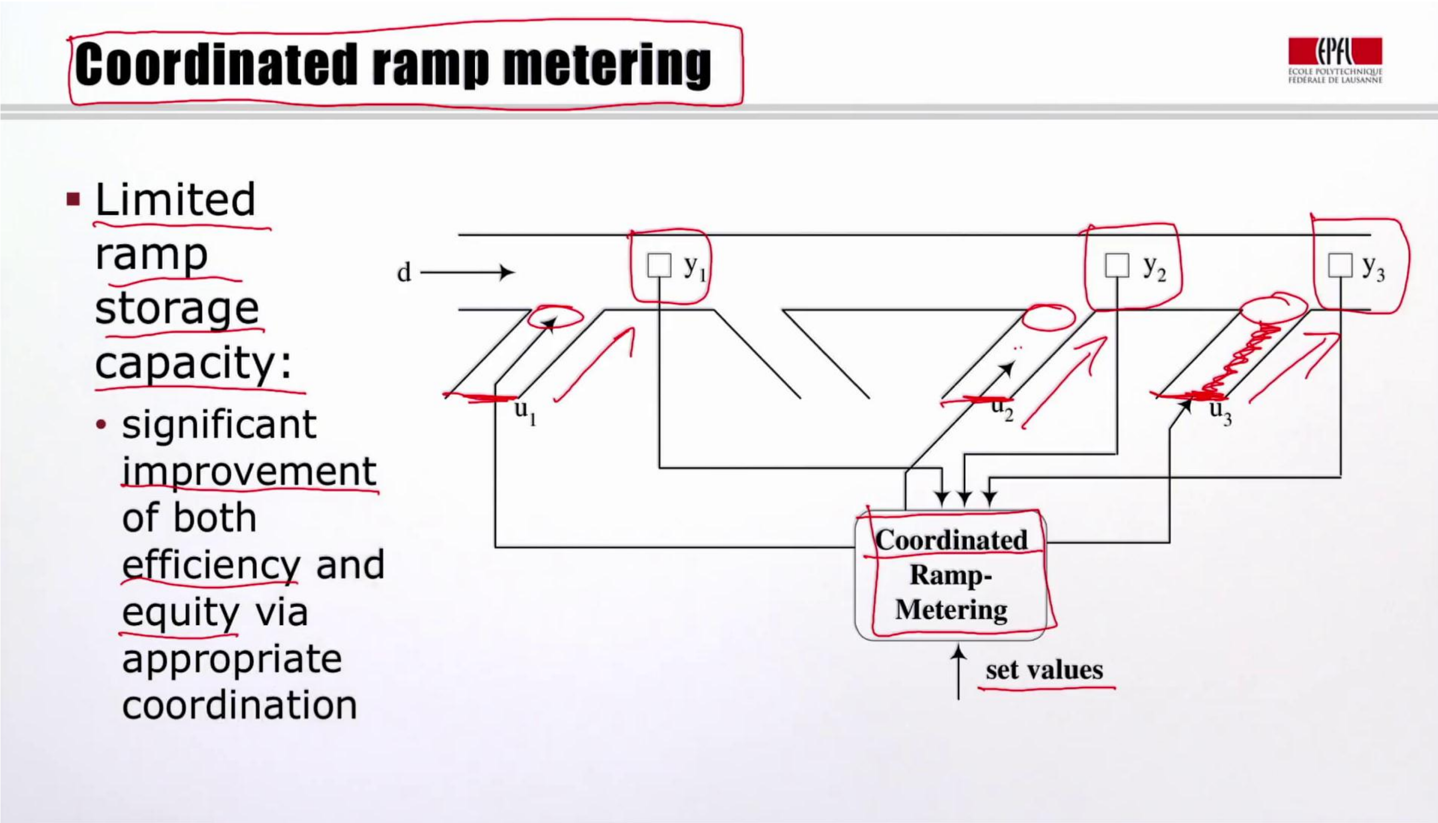


I would like also to discuss the implications of ramp metering around the world. Nowadays, we have too many implementations around the world. In North America, we have more than 3,000 ramps that are metered so these meters start during the congestion, there are not active all the day. When it is an off peak hour, they are not activated but then, when we have the peak hour and the congestion starts, we activate the ramp metering. More recently, we have application of ramp metering in Europe, Israel, New Zealand, Japan, Australia and all over the world. People accept nowadays that ramp metering is beneficial for highway traffic. Of course, ramp metering has some control limitations. First of all, we don't have too many ramps that are available to control. So the amount of ramps is limited and then sometimes, you may want to apply some limited ramp flows. I cannot restrict the flow completely but I have some minimum flow that I need to get into the highway. As I discussed before, there is this physical length of the ramp that defines the maximum storage capacity in vehicles and after this point, I have interference of the queue of the ramp with the surface street traffic in the neighboring arterials.

Notes

Summary

25m 43s

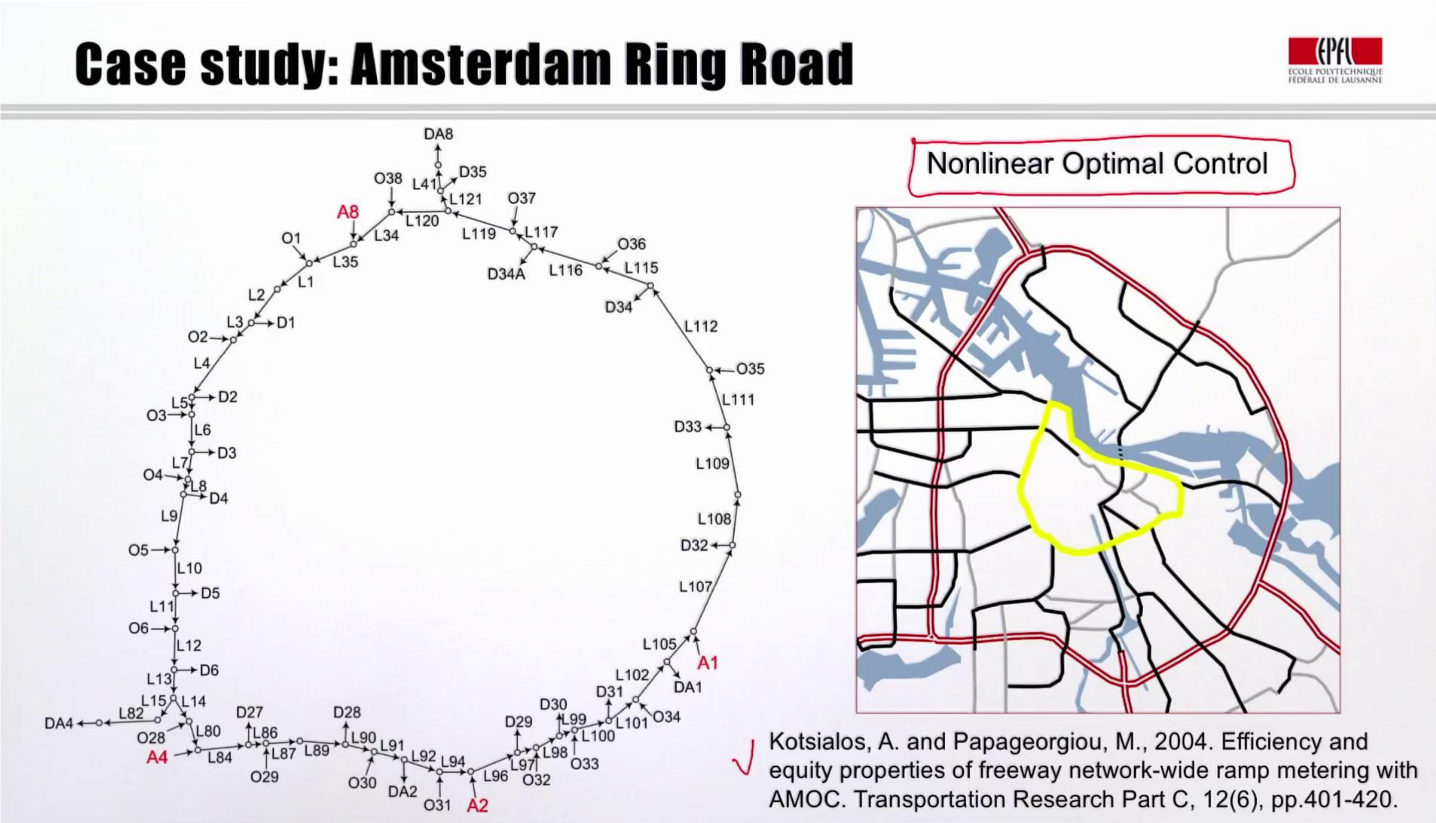


Given this limited ramp storage capacity, what could I do better? I would like to discuss in this slide what we call coordinated ramp metering. So instead of doing this local ramp metering that I discussed in this slide, I can do some kind of coordination between ramps. If I have a highway network here, I have 3 ramps with some storage capacity in each of them and I can apply ramp metering. I can get measurements from the downstream locations and because I have this storage capacity here at the ramp, I have a limit to the ramp metering that I can apply. But if I don’t think locally and I think more globally, if I look at the highway as a whole, I can do some coordination between these ramps. Imagine I don’t have enough space here in this ramp, I have reached my storage capacity but I have space in this ramp. So maybe I can start ramp metering in this ramp and ask for some space. So by developing coordinated ramp metering approaches that work in a similar way as the local one but I have some kind of coordination, I can improve the situation. Again, the idea is that I have some set values that are the same as before. It has been proven that by some coordination, I can have some improvement that would show you the equity between the ramps.

Notes

Summary

27m 12s

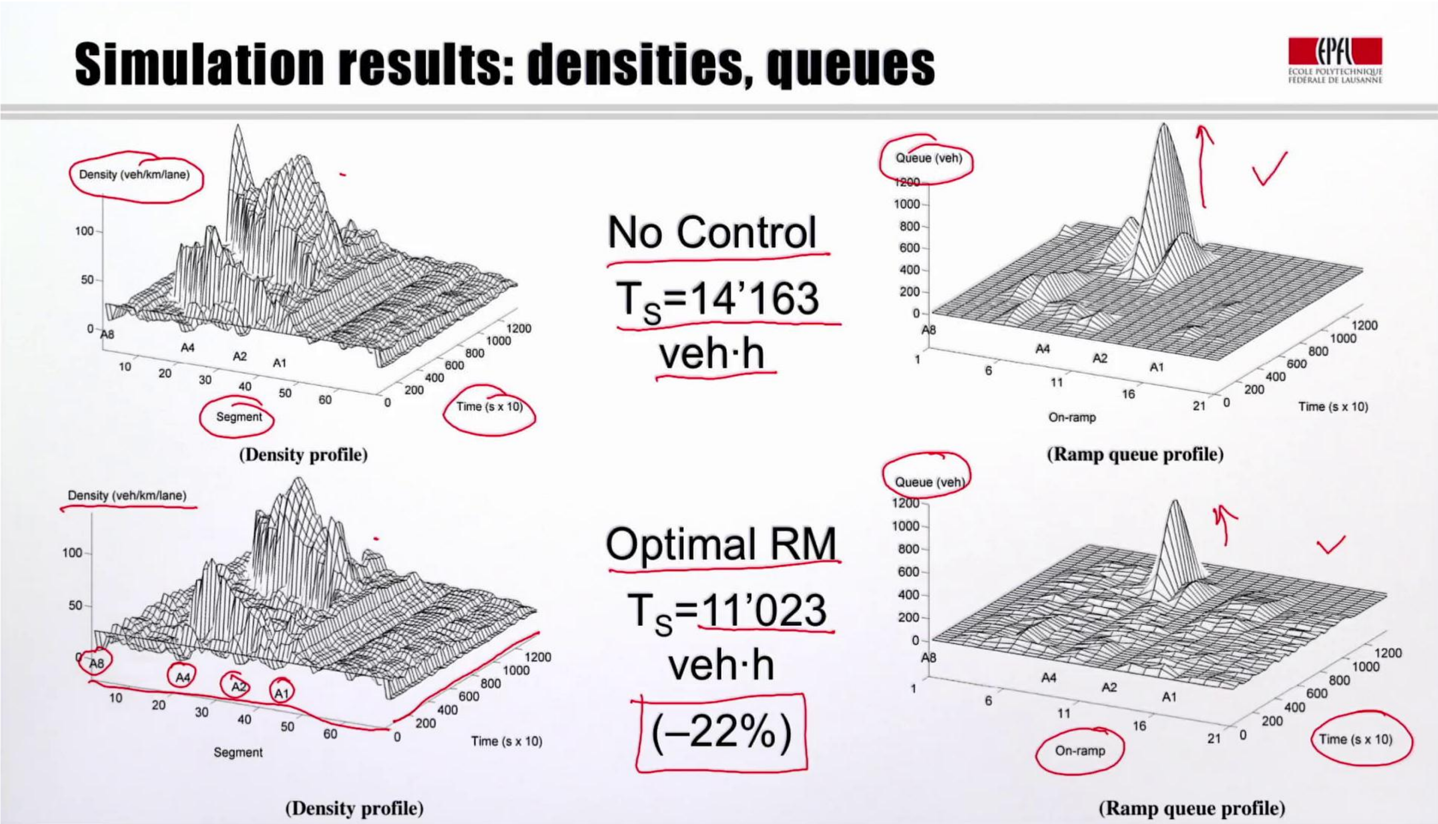


I would like to close this video with2 case studies of coordinated ramp metering. The first one is the ring road around Amsterdam. I have in this map the city of Amsterdam and around it, there is a ring road that I see here like in many European cities, which is a highway. I know that this highway is connected with 4 other highways. I have 4 other locations here that I have highway to highway connection. In the rest of the networks, I have on- ramps and off- ramps. So I have here on the left the simulation highway of this model, I have all the on-ramps and all the off-ramps of the 4 highways. There is a simulation study that applies non-linear optimal control in order to do coordinated ramp metering in this ring road. This is the reference of the paper that I got this results and here are the results of the simulation experiment.

Notes

Summary

28m 53s

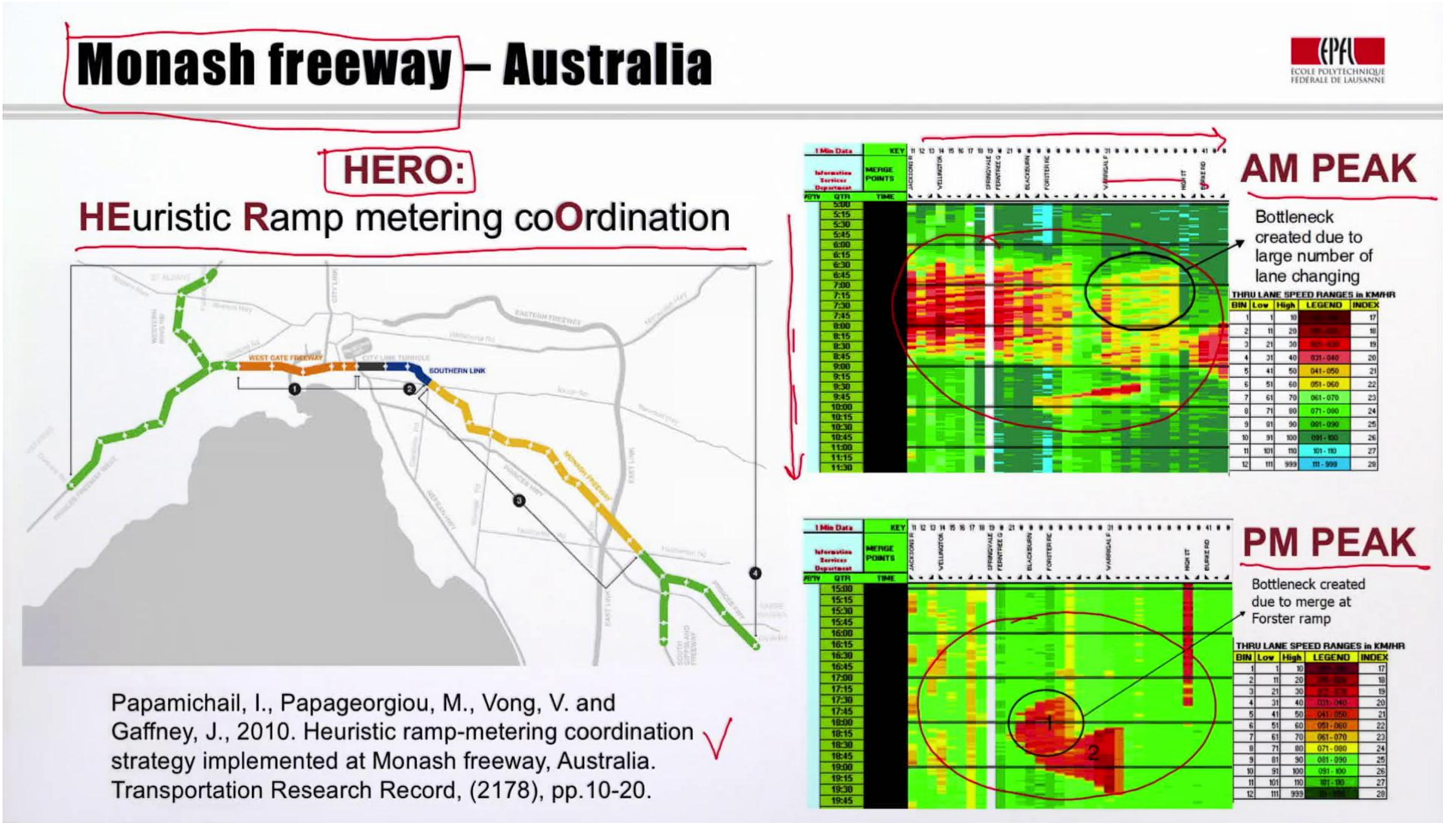


In this 3 dimensional diagram, I can see the space, the time and the density in all the highway networks. This is a no control case on the top and on the bottom is where I apply the optimal nonlinear coordinated ramp metering. Here, I can see the 4 highways. These are all the kilometers of the highway. This is the time, the duration of the simulation and this is what happens with the density if I do ramp metering and if I do not do ramp metering. On the right, I have all the queues of this on-ramp of this highway. So I have here, the on-ramp, here the time and here, the queue in vehicles. So this is the ramp metering case and this is the no control case. So I can see the queue that builds here and the queue that I have in this scenario that I do ramp metering. Before I evaluate the values of this simulation, I can compute the total time spent in the no control case, which is this vehicle hours traveled and I can compute the same matric for the ramp metering case. I can see that I got some 22% improvement by applying coordinated ramp metering in this network. Again, these results refer to the paper of the previous slide.

Notes

Summary

29m 58s



The last case study is from Australia Melbourne and we have this Monash freeway and we apply a strategy of ramp metering that I known as HERO; Heuristic Ramp Metering Coordination. You can refer to this paper for more details. So this is basically applying local ALINEAS in the ramps but there is some Heuristic coordination between the ramps so there is a coordination of the ramp meters. In this network, we have some simulation results again so we can see the AM peak of the network and the PM peak of the network. Here, we have space on this axis and we have time on this axis so we can see all the highway and all the simulation and we can see the congestion that forms here. In order to run this simulation, we use macroscopic flow modules for highways and by applying this HERO, we can evaluate the performance of our controller.

Notes

Summary

31m 31s

Ramp metering – Summary

In this video, we have discussed about ramp metering that utilizes real time data from traffic sensors and applied feedback control laws in order to manage the mobility in highways. You can have a look at the class material whether you can find additional content and practice exercises. See you soon.

Notes

Summary

32m 47s