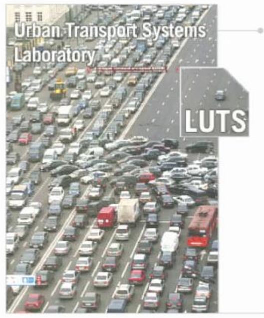
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

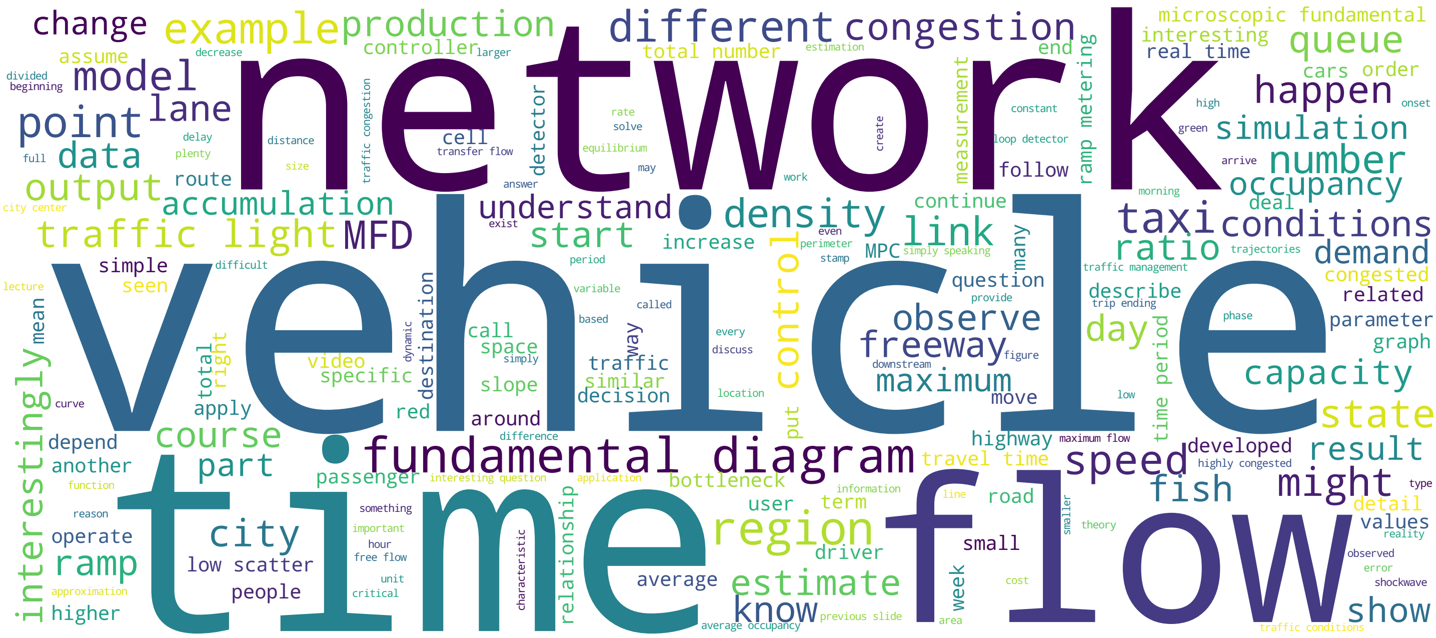
Macroscopic Fundamental Diagram:

Existence, Physical Properties and Dynamic Modeling

Intro to traffic flow modeling and ITS

Prof. Nikolas Geroliminis





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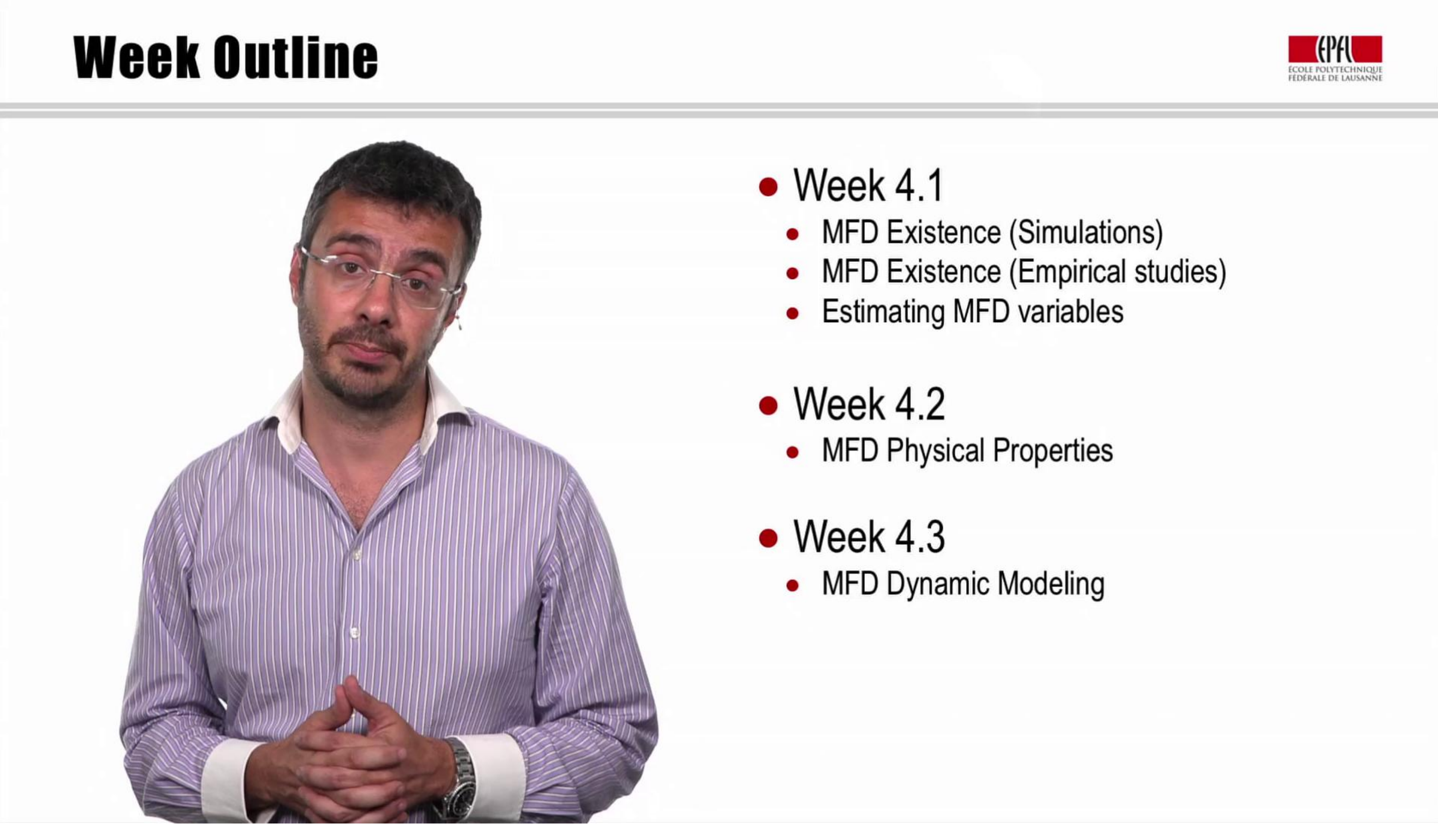
Video



Welcome. Understanding of modelling traffic congestion is a challenging task. Depending on the type of application, there are traffic models of different regularity, from very detailed to aggregated. This course will focus on the microscopic fundamental diagram, which is an aggregated way to model and understand traffic, which has recently attracted a lot of attention, because it's a very intuitive and elegant way to deal with congestion. During this week, we will see different aspects of the microscopic fundamental diagram that from now on we will call it with each initials MFD. As we've seen the course outline, we will easily investigate and understand under what conditions a microscopic fundamental diagram exists through simulation studies, but also through empirical data. Also understand what are the traffic variables involved in the MFD and how they can be estimated? Later we will see under what conditions and physical properties an MFD will provide a good representation of city traffic. While in the end of this week, we will deal with the dynamic characteristics and dynamic properties of these two.

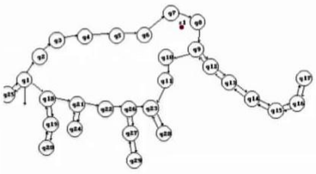
Notes

Summary

0m 05s

WHY A NETWORK LEVEL APPROACH?

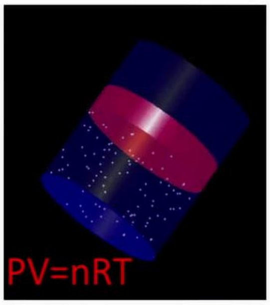
- Humans make a lot of choices - routes, destinations and driving behavior (unpredictability)
- Not a clear distinction between free-flow and congested states at link level (complexity)
- Decentralized control is not efficient for highly congested systems (controllability)



"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk".
JOHN VON NEUMANN

- Move from PREDICTION to OBSERVATION
- Develop physically realistic models of urban congestion

PROPOSE→ MONITOR→MODIFY



An important question is, why we need a network level approach? The reason is when we have to deal with a very large city, thousands of roads and sometimes millions of people move moving around, it's very difficult to be able to predict and understand the movements of every individual. So there is a high degree of unpredictability on how people choose their destinations, their routes and what is their driving behavior? At the same time, what we know is that traffic, the lower level, so the level of one link has also significant complexity. So it's not very easy to separate, congested from uncongested conditions. And the third important reason is that when we deal with very large networks, where we might have to coordinate and optimize some hundreds of thousands of traffic lights, do this in a global and coordinated way, given the existing methods is very difficult because it might require too much time and we want to make decisions in real time. By utilizing a network level approach without knowing the details for individual travelers, we can move from prediction to observation.

Notes

Summary

1m 25s

WHY A NETWORK LEVEL APPROACH?

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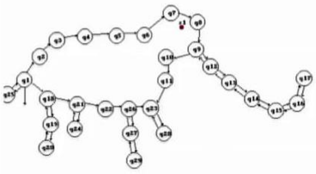

"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk". JOHN VON NEUMANN

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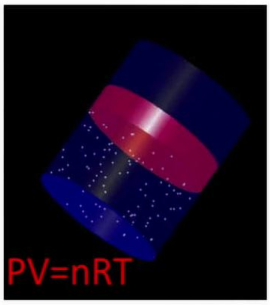


So we can use different sensors to observe the state of the system and utilize the sensors to model properly traffic congestion and how it changes over time and space, but also be able to develop traffic management schemes that can improve mobility. And actually this method have some degree of similarity with other aggregated models that are used in sciences like physics and chemistry. So here for example, within the general gas law, where we might not be able to know the exact location of each individual particle, but we're able to model and understand the aggregated state by using aggregated variables like pressure, volume and temperature.

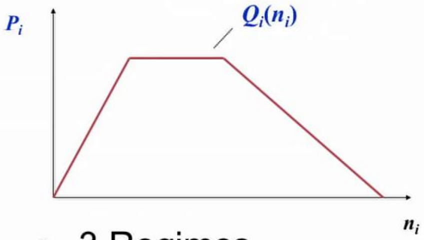
Notes

Summary

2m 46s

Fundamental Diagram (FD) for a link *i*

- Accumulation : n_i (vehs)
- Travel Production : P_i (veh-km/hr) - **VKT**
- Output-Trip completion rate O_i (vehs/hr)



- 3 Regimes

I : Undersaturated
II : Efficient
III : Oversaturated

Let's look at the fundamental diagram of an individual link 'I' that has a traffic light at it's downstream end. And we'll use the following traffic variables to describe traffic conditions. First is the accumulation, which is the number of vehicles. And let's say that this quantity is the other ads over a period of time. That might be a couple of minutes equals let's say to the cycle length of the traffic light. We cover the travel production, which is the vehicles kilometers travel, but you need time by all the equals moving in this link and then we have the output on the trip completion rate or y, which is the age that the vehicles are exiting the link. So if we look at the fundamental diagram between Pi and Ni, and I can also say that the fundamental diagram between Oy and Ni will be similar. What we observe, we observe three regimes. So there is an under saturated regime where the more vehicles on the link, the higher the production or the output. Then we have the second regime, which is the efficient regime where the traffic light operates at capacity. And then we have the over saturated regime.

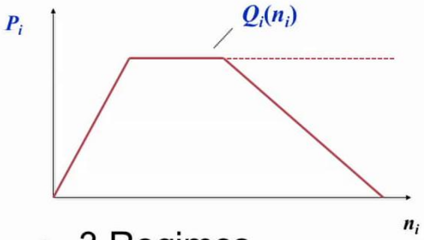
Notes

Summary

3m 33s

Fundamental Diagram (FD) for a link *i*

- Accumulation : n_i (vehs)
- Travel Production : P_i (veh-km/hr) - **VKT**
- Output-Trip completion rate O_i (vehs/hr)



- 3 Regimes

I : Undersaturated

II : Efficient

III : Oversaturated

Growing queues from the downstream link block the arrivals

Where in this over saturated regime, as you have more vehicles in the network, then what will happen is that the output of the production will decrease with a number of vehicles. This might not sound intuitive because what somebody might expect is that as you continue to add more vehicles in a link, this link will continue to operate at capacity so the production in the output will remain constant. But in reality when we're in networks, what happens? Well, we have links that are interacting with each other. So we have growing cues from the downstream link that block the arrivals upstream.

Notes

Summary

4m 47s

Fundamental Diagram (FD) for a link *i*

- Accumulation : n_i (vehs)
- Travel Production : P_i (veh-km/hr) - **VKT**
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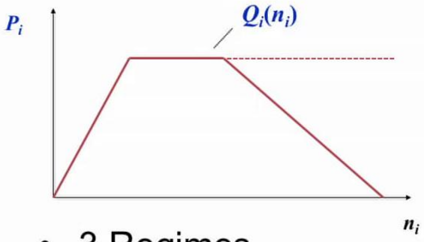
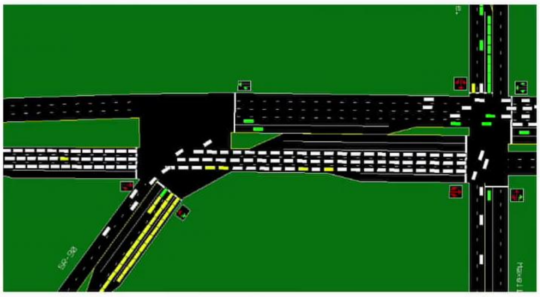




- 3 Regimes

I : Undersaturated
II : Efficient
III : Oversaturated
Growing queues from the downstream link block the arrivals

And here is a video explaining this show. Look at this traffic light where when it becomes red as vehicles grow and block the departures from the downstream traffic light. So this pillbox have as a result that the ups from upstream ling has a smaller output.

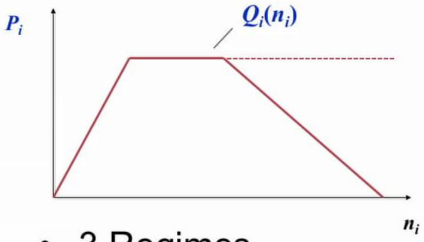
Notes

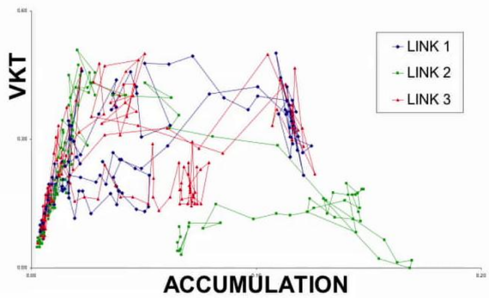
Summary

5m 28s

Fundamental Diagram (FD) for a link *i*

- Accumulation : n_i (vehs)
- Travel Production : P_i (veh-km/hr) - **VKT**
- Output-Trip completion rate O_i (vehs/hr)





- 3 Regimes

I : Undersaturated

II : Efficient

III : Oversaturated

Growing queues from the downstream link block the arrivals

If now we look at data that have been collected from micro-simulation between vehicles kilometers travel and accumulation for three specific roads, what is interesting is that we actually see the trapezoidal SAPE of the fundamental diagram, the upper envelope, but at the same time there is a cloud of points in between, which actually these points represent transit states and non-steady state the conditions. So interestingly, what we say in theory is different that what we observed with different types of data for a single link. But the situation might be different when we aggregate many links together.

Notes

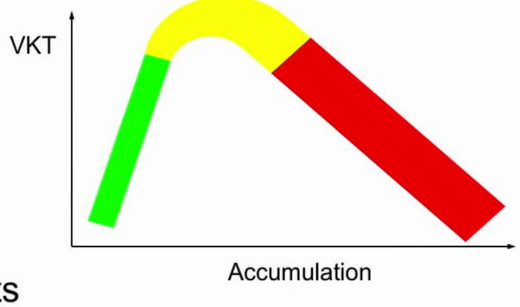
Summary

5m 52s

Theory: Generalization to networks

$$P = \sum P_i = \sum Q_i(n_i) \cong Q\left(\sum n_i\right)$$

AGGREGATE BEHAVIOR
=
SCALED UP VERSION OF LINK BEHAVIOR



- An MFD exists
- Trip completions / Network flow ≈ Constant

So the theory, when we try to generalize that individual fundamental diagram to networks, what we seem to have, we have that the total production of the network is the sum of the production of the individual links. If we're going to see that, that each of these liens have approximately a fundamental diagram Qi(Ni), like we had in the previous slide, then what we claim, we claim that under some conditions then what we can have, we can have the aggregated behavior to be the scaled up version of the link behavior. So the total production p will depend on the total accumulation of the network. Obviously if we look at this equation to go from here to there, it means that Q is a function with inner characteristics. But as we know, the fundamental diagram is not a linear function as it has been increasing and constantly decreasing part. So this will happen only if most of the links over the network belong in the same branch. So if most of the links of the network are in the uncongested or in the congest regime, which we can approximate with straight lines, then we can also see that this approximation will also be valid. So what we want to investigate?

Notes

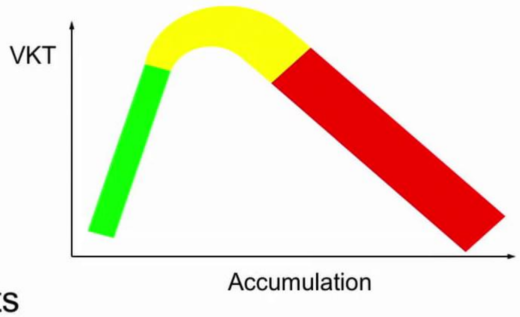
Summary

6m 35s

Theory: Generalization to networks

$$P = \sum P_i = \sum Q_i(n_i) \cong Q\left(\sum n_i\right)$$

AGGREGATE BEHAVIOR
=
SCALED UP VERSION OF LINK BEHAVIOR



- An MFD exists
- Trip completions / Network flow ≈ Constant

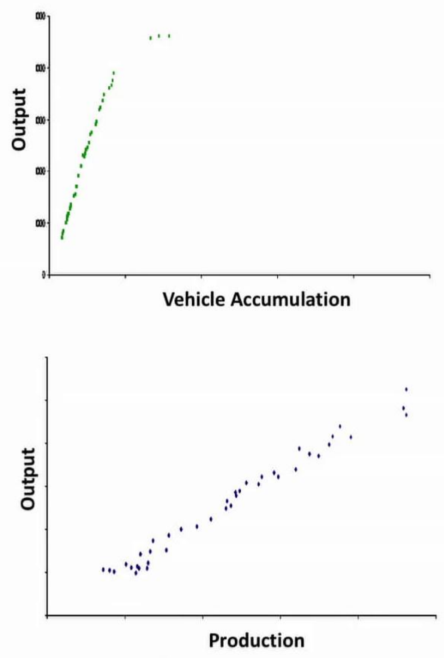
We want to investigate under what conditions, a microscopic fundamental diagram connecting the network production with a total number of vehicles exists. And then the second thing that we will see in this lecture is that actually the two variables we defined before the trip completions or trip endings and the network flow or production, they have a ratio which is about constant. And this constant quantity is related with the average three planks of the vehicles.

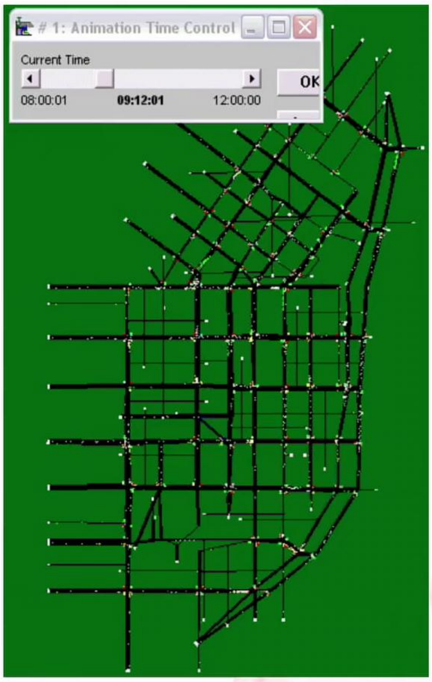
Notes

Summary

7m 52s

MFD (Simulation evidence)





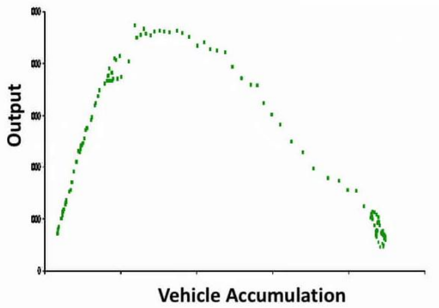
Let's try now to look and understand the microscopic fundamental diagram through a realistic simulation of downtown San Francisco. Which as we see on the right is a network with about 500 links and around 100 and traffic lights, sayings between green, yellow, and red face. So when did we just starts, we will see that the demand is very low in the beginning of the morning peak and as time passes, demand increases. And what we will see in a synchronized manner, we will see how the output of the vehicles is related with vehicle accumulation and how the output of the vehicle, so the trip ending is related with the trip production of the vehicles, every let's say five minutes. Let's start the video. So in the beginning of the simulation as the demand is low, we see that there are very few vehicles moving into the network and during this time the output is small and as mentioned, the vehicle accumulation is more. But as during the course of the day the demand increases, what we will start observing, we'll start observing crucial vehicles at some traffic lights. And this is about the time that we started seeing the first queues. So let's see, for example, the north of the network, some queues will start to be developed.

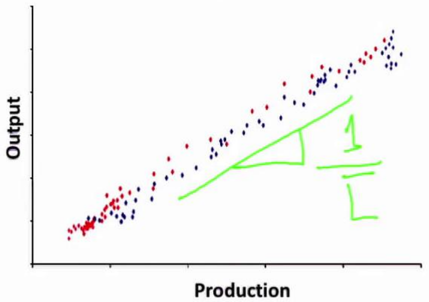
Notes

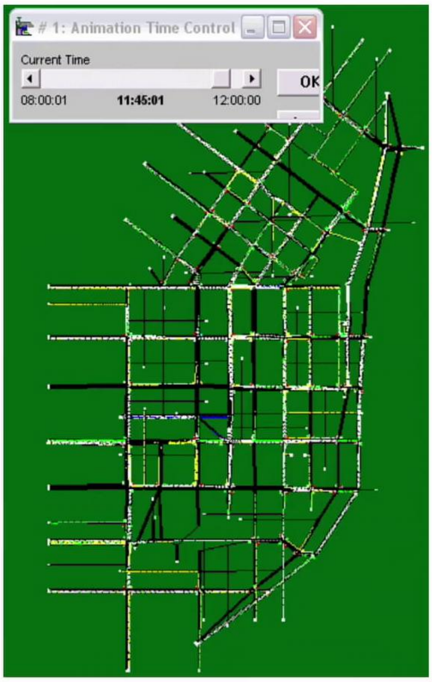
Summary

8m 27s

MFD (Simulation evidence)





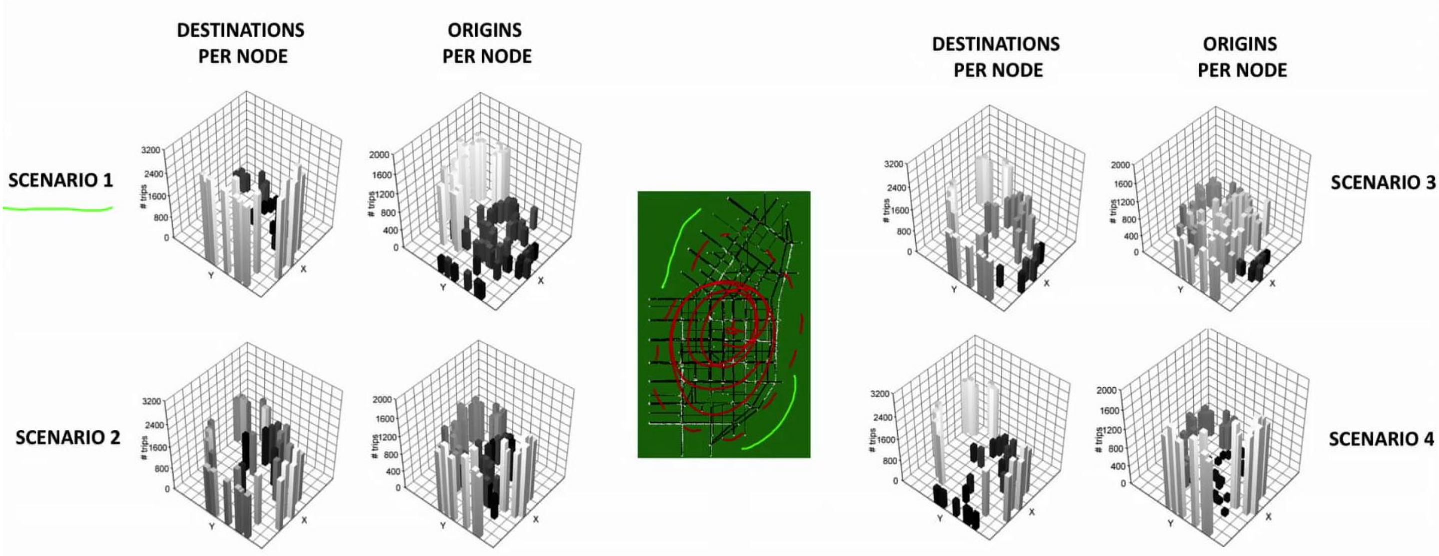


And also in this part. And interestingly, the output of the network continues to increase and more queues are developed but after some talk point, we start to having spill bucks. So queues that propagate and block next links. This will have as a result the network output after some point to start decreasing, because we'll have plenty of vehicles in the network and this is about the point that this happens in this diagram. And as we continue to load the network with more and more vehicles, more queues had developed, the outputs significantly decreases and actually by the end of this simulation, we'll almost reach a state of gridlock. What is interesting, if we look at the graph below between output and production during all this evolution of states from uncongested to congested, there is a linear relationship that describes it very well. And actually, if we look at the units between the ratio of output and production, we will see that this line here has units of one over kilometers, so it is one over the average triplets. Please also note that when the network is highly congested, some of the links are full, but also some of the links like this one is absolutely empty, because vehicles due to spill bugs cannot read this specific roads.

Notes

Summary

9m 53s



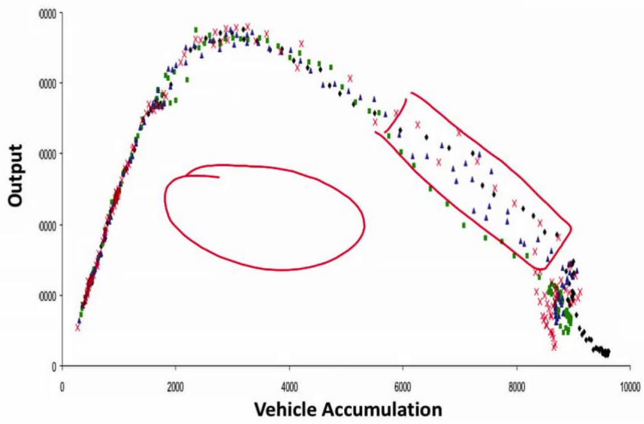
So in the previous video, we saw that an MFD between accumulation and production or output has a significantly low scatter compared to the individually in fundamental diagram. But how sensitive is the MFD to different demand profiles? To answer this question, we make many different simulations like the want in the previous video where we saying, the distribution of origins and destinations in the city. So for example, in scenario one, what you see, you see that there are plenty of origins that start from this part of the network and they are finish in that part of the network as we can see from these graphs. Where, if for example, we look at scenario three, we see that, origins are almost evenly distributed in the network and the destinations are more on the boundary and if you insight.

Notes

Summary

11m 18s

MFD – Sensititvity to demand



MFD is a property of the infrastructure
INDEPENDENT OF O-D TABLES

So if we look for MFDs for the four different scenarios of the previous slide, interestingly, even if the demand is very different, all MFDs follow the same pattern. And what we see, we see very low Scatter. And there's no points below which is the case for the individual fundamental diagrams. Interestingly, what we see, we see some high scatter when were in the highly congested regime. And this is you to the chaotic behavior of transportation networks. And if we want to say this in simpler words, please refresh your memory from the video a few minutes ago, where we noticed that some links were full and some links were empty under highly congested conditions. So this doesn't happen in an identical way under different origin destination patterns. And this is what creates this scatter in these conditions. So MFD is a property of the network and is not very sensitive to different origin destination tables, but this is an excellent property that can be utilized later for traffic management.

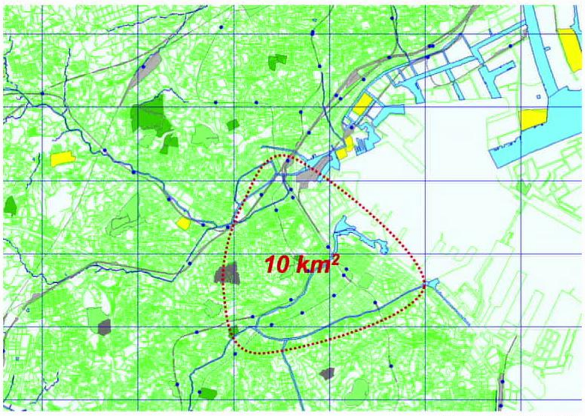
Notes

Summary

12m 21s

Real World Experiment: Site Description

- **Fixed sensors**
  500 ultrasonic detectors
  - Occupancy and Counts per 5min
- **Mobile sensors**
  140 taxis with GPS
  - Time and position
  - Other relevant data
  (stops, hazard lights, blinkers etc)
- **Geometric data**
  Road maps
  (detector locations, link lengths, intersection control, etc.)



(Dec. 2001 data)

Geroliminis, N. & Daganzo, C.F. (2008). Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings, *Transportation Research part B, 42* (9), 759-770

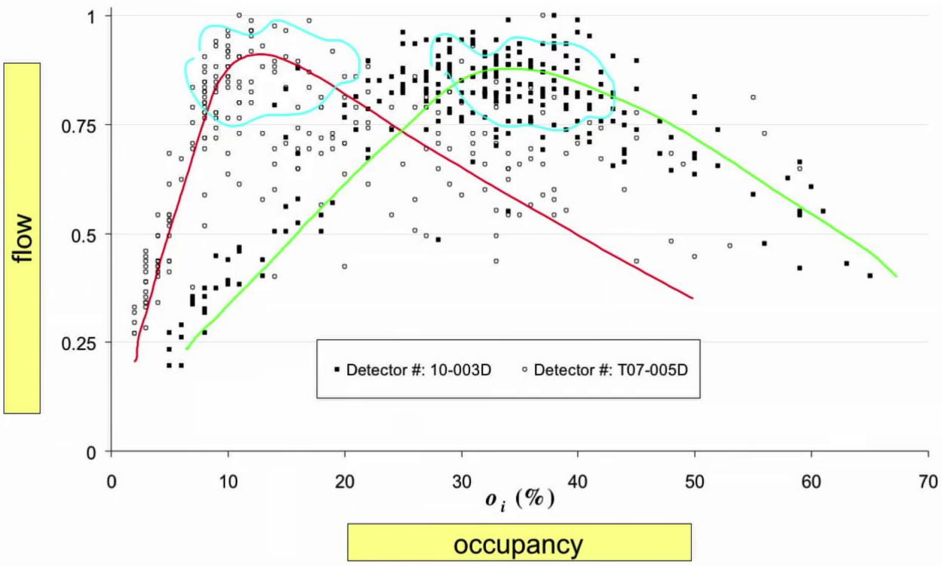
Nevertheless, simulation contains a significant number of assumptions that might not be fully realistic. So it would be more interesting to see if these MFD or cures and exists for real time networks. And we were lucky enough to have plenty of data for a downtown to the city center in Japan that helped us to better understand the concept of the MFD. So during this experiment, we had data from about 500 detectors that were providing all occupancy and counts every five minutes distributed in the city center. We had about 140 trajectories of taxis that were giving their time and position every few seconds for the course of a few weeks. And we also had geometric data about this specific network.

Notes

Summary

13m 38s

Single Detectors



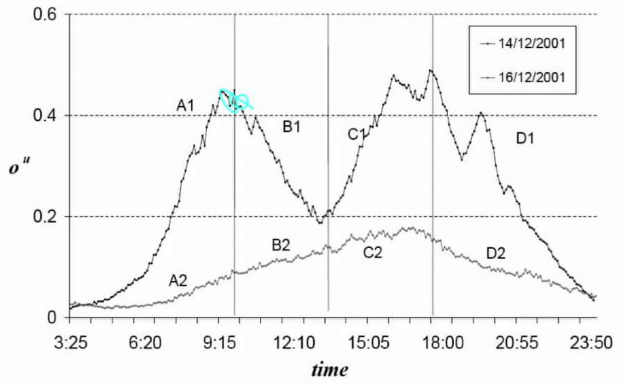
Let's first look at the fundamental diagrams for two individual locations from two single detectors between the dimension and flow. So zero is the minimum and one is the maximum flow and the occupancy, which shows the amount of time that [14:54 inaudible] is occupied by vehicles. So interestingly, both detectors produce a fundamental diagram that has a uni-model relationship. But what is very interesting is that there is a significance scatter, especially for the value of [inaudible] where flow flows maximize. So this shows that the individual FDs cannot represent very well traffic conditions and especially under transit states.

Notes

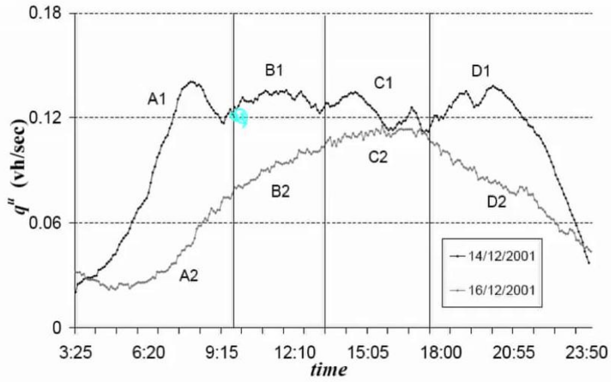
Summary

14m 35s

Space-Mean Flow and Occupancy



Average Occupancy by time-of-day



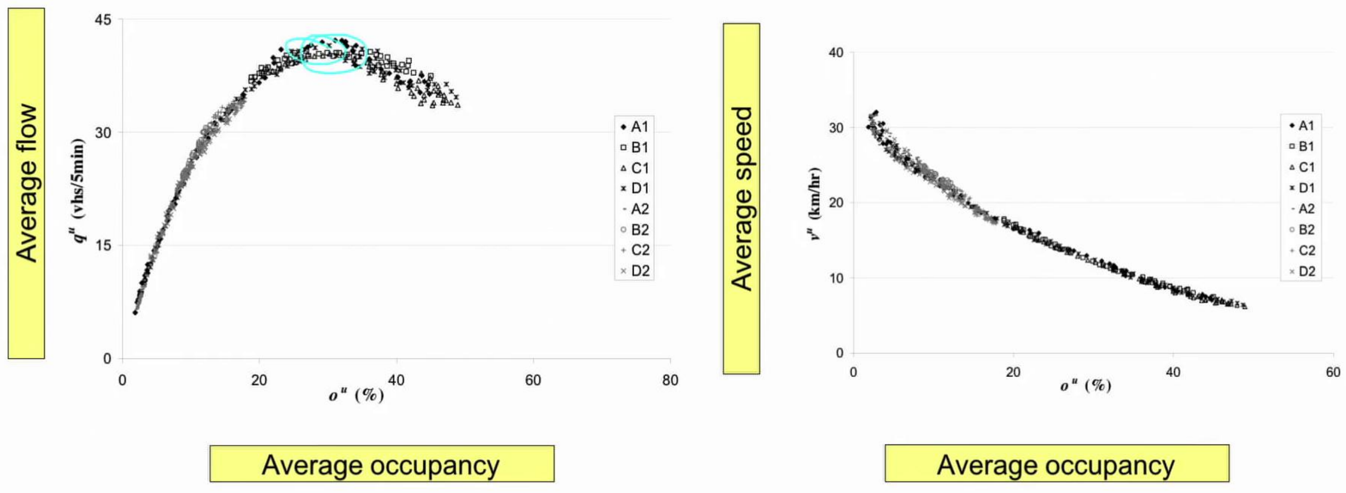
Average Flow by time-of-day

But let's look what happens when we aggregate things. So what do we see here, we see the space mean flow and occupancy from 500 detectors during the course of two days. So the 14th of December is a week day with high demand when the 16th of December is a weekend. So interestingly if we look at the average occupancy on the left figure, occupancy increases with time and it reaches a maximum value during that time around 9:30, then it decreases and it increases again during the onset of the evening. While at the same time, what we see, we see that the average flow doesn't follow an identical profile. So what we can observe, we can observe that when occupancy is maximum, flow cause already decreased and is not maximum, which is a sign that the network operates under congested conditions. And what we're going to also notice, we can notice that over the weekend, which is the other day, the network is not so congested and the pattern is smoother and we don't read so high values of occupancy. So what do we do? We separate the course of the day to for time periods for each day, which represent the onset and the offset of the morning and the onset and the offset of the evening for the two days. So in total we have eight time periods. So let's try to see the microscopic fundamental diagrams for these eight time periods.

Notes

Summary

15m 27s



Which eight time periods I represented with the different symbols in this slide. So very interestingly, the scatter of the individual detectors this appear and we have a very neat curve between average flow and average occupancy, but also if we look at average speed over average occupancy, again, we have a care with very low scatter. And interestingly, these different symbols over here are mixed to each other, which actually means that the MFD is not so sensitive to different demand patterns that occur during this different time periods. So MFD is a property of this network. It has very low scatter and it can also be utilized to develop traffic management techniques. Because if we ask ourselves, what is the ideal point for the city to operate? Most probably we want to operate around here where flow is maximum.

Notes

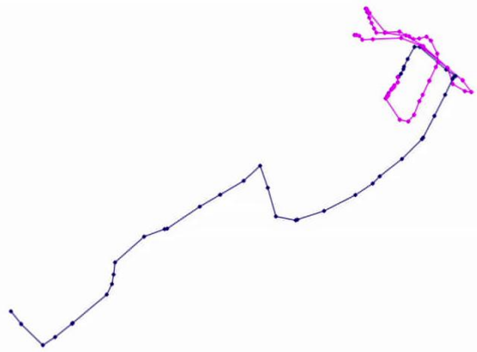
Summary

17m 12s

Fusing taxi and detector data

An MFD exists on the part of the network covered by detectors. What about the whole network?

1. Filter for passenger-carrying taxis
2. Estimation of accumulation and speed
3. Results



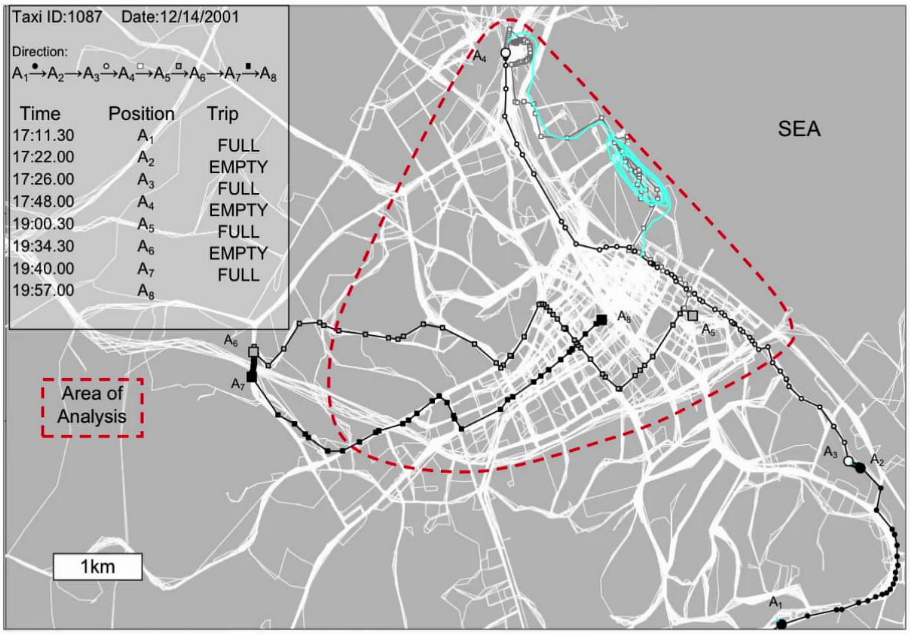
So what we have seen is that an MFD exist on the part of the network covered by the detectors. But an interesting question is, what about the rest of the network? So to answer this question, we fused together the taxi and the detector date. Taxis are considered good proxies with normal vehicles, but we should not forget that when they search for passengers, they might have a completely different behavior. So we filter these types of data and we only keeping out analysis passenger carrying taxis. And here we see an example. So this is the trajectory of a taxi and each dot shows the position every 30 seconds. So the blue line shows a passenger carrying trip, while the pink line, shows a taxi trip when the taxi searching for the passenger. So after we apply a filter which is provided in more details in the associated publication, which you can find in the class material, with them, tried to estimate in their accumulation in the speed and then we can see some results by fusing all this data.

Notes

Summary

18m 14s

Illustration of filter results



Let's look first at an illustration of the filter results for the taxes. In this figure we see the trajectory of a taxi during a period of more than three hours. We see that there is a sequence of full and empty trips of the taxi as expected. So as an example, the taxi starts from point A1 and it delivers a passenger to point A2 and then it becomes empty for some period of time, which stays locally to shirts. And then we have another trip from A3 to A4. And interestingly after that, the taxi becomes empty, but it has a very [20:03 inaudible] route where it searches for the passenger. So these are the parts of the data that we don't consider in our analysis, because we consider that during these times taxis are not representative of the overall movement of different vehicles of the network.

Notes

Summary

19m 22s

Estimation of accumulations and speeds

An interesting question is how we can estimate the number of vehicles we have in a city by utilizing the data from loop detectors and taxis? And actually this question is very similar if we want to answer how many fish we have in a lake? So let me try to describe you the analytics. So let's say that we want to estimate the number of fish in Lake. The you can do it is we go one day for fishing and let's say that we're lacking, we're able to caught 100 fish. So after we do that, we put a stamp for each of these fish and then we throw them again inside the lake. Next day we'd go again for fishing. And let's say, we caught another 100 fish. So what we'd say? We'd say, how many of these fish have a stamp? And by knowing the ratio of fish with and without stamp, we can extrapolate an estimate the total number of fish.

Notes

Summary

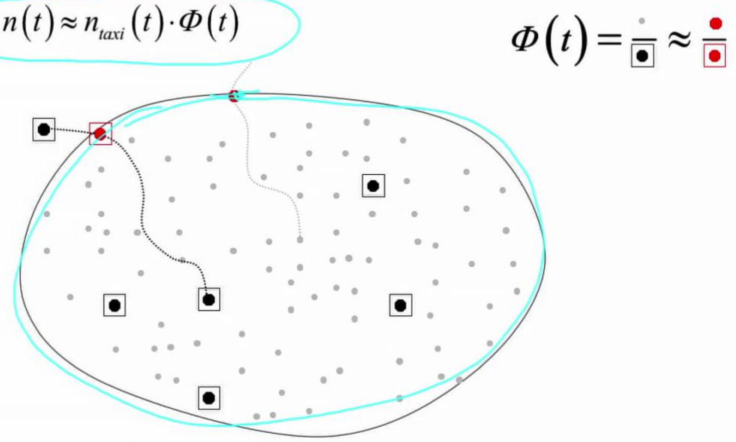
20m 19s

Estimation of accumulations and speeds

Conjecture: Passenger carrying taxis use the same parts of the network as cars

Then: $u(t) \approx \bar{u}_{taxi}(t)$

$n(t) \approx n_{taxi}(t) \cdot \Phi(t)$



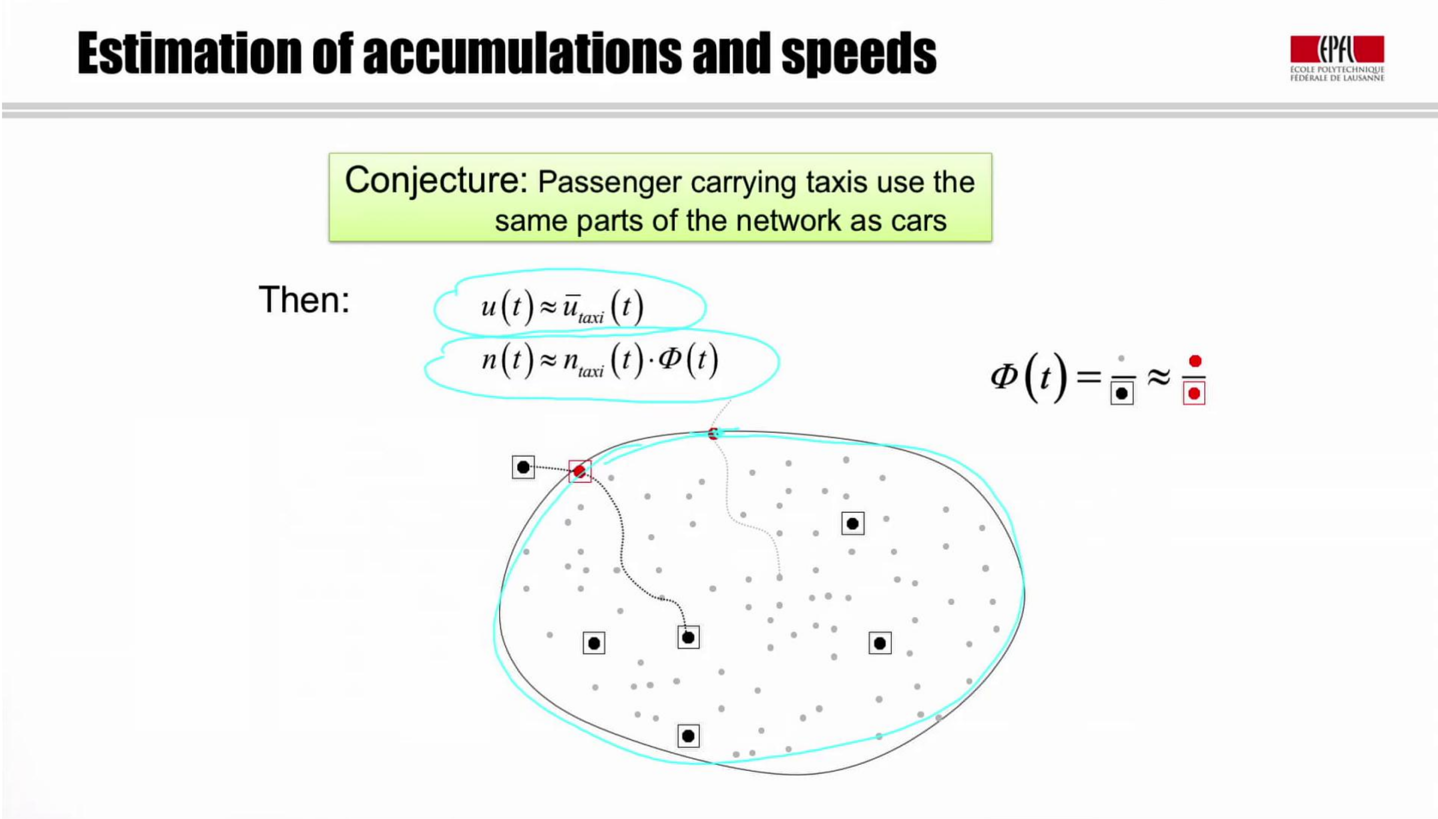
So exactly the same we can do here, but we have to replace fish with cars. And what is fishing? Fishing is actually the taxis because when we catch the fish and we put a stamp is like, we have a taxi, where taxi has a GPS and we're able to know it's exactly trajectory. So these dots with a square around are taxis that are moving in the city and we know how they're moving. While the single dots, like the gray ones are the simple cars that were not able to observe unless they cross a loop detector. So let's assume that in the perimeter of the city, we'll have some loop detectors and this is where we observed a car. If we want to estimate the ratio of cars and taxis in the whole city and taxis are with gray dots because actually we don't observe them while the black dots of taxis, we can see them. This ratio is equal to the ratio of cars and taxis that are crossing the perimeter of our city where we have looped detectors. And this is the analogy that we can make with the fish. So this is a proper way to estimate this ratio. And then by applying a simple formula, we can know the total number of vehicles that we have in the city as the total number of taxis multiplied by that ratio.

Notes

Summary

21m 24s

Estimation of accumulations and speeds



$$u(t) \approx \bar{u}_{taxi}(t)$$

$$n(t) \approx n_{taxi}(t) \cdot \Phi(t)$$

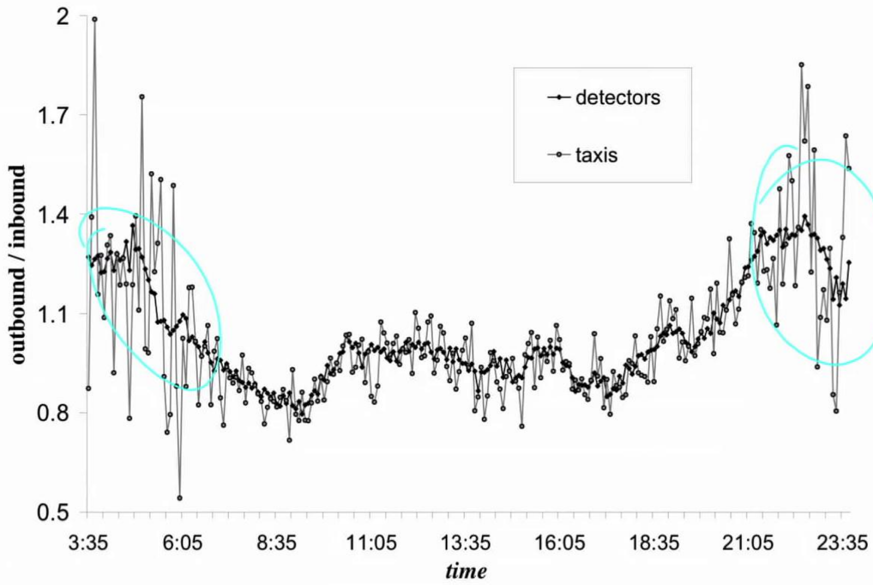
And also we can assume which is reasonable that the speed of the vehicle during your time period is approximately equal to the speed of passenger carrying taxis. What is the problem with this approximation? This estimation will be quite accurate. You vehicles are quite homogeneously distributed in our city and the same applies for the fish. The fish should be quite homogeneously distributed in the lake so that the experiment with the fishing, we can estimate accurately the total number of fish.

Notes

Summary

23m 00s

Full taxis vs. cars



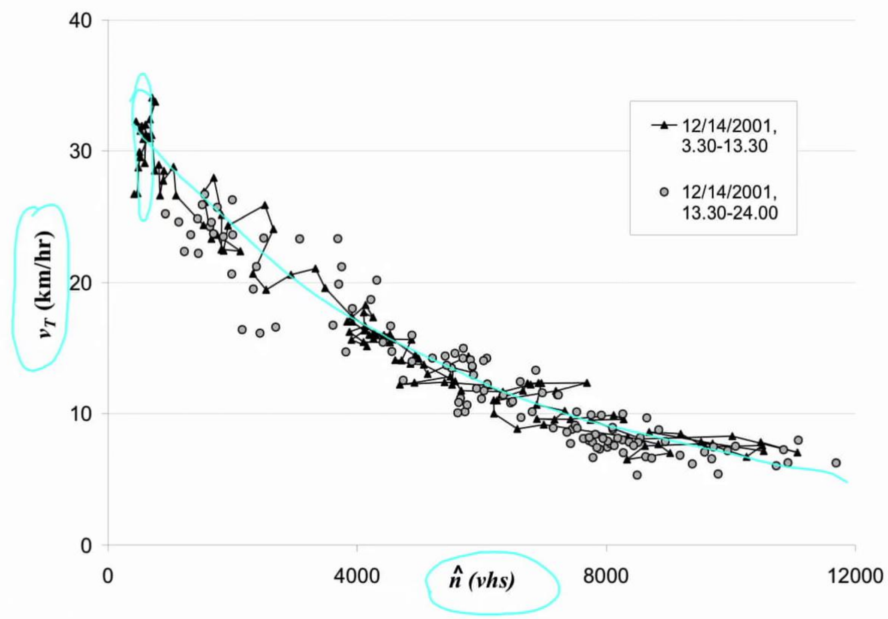
So after we do that by fusing taxi detector data, we can estimate different quantities. But before we do that, an interesting question is how taxis and normal cars represent similar conditions? So to do that, we looked at the ratio of outbound and inbound traffic in the perimeter of the city by the detectors and by the taxis. And what is interesting, we see that we follow a very similar trend, but this trend has a very high scatter during the night. And that is a simple explanation. This is because we have very few taxis. So as our sample size is more, waltzed expect our estimation to have a higher noise.

Notes

Summary

23m 39s

Taxi and detector data: Results



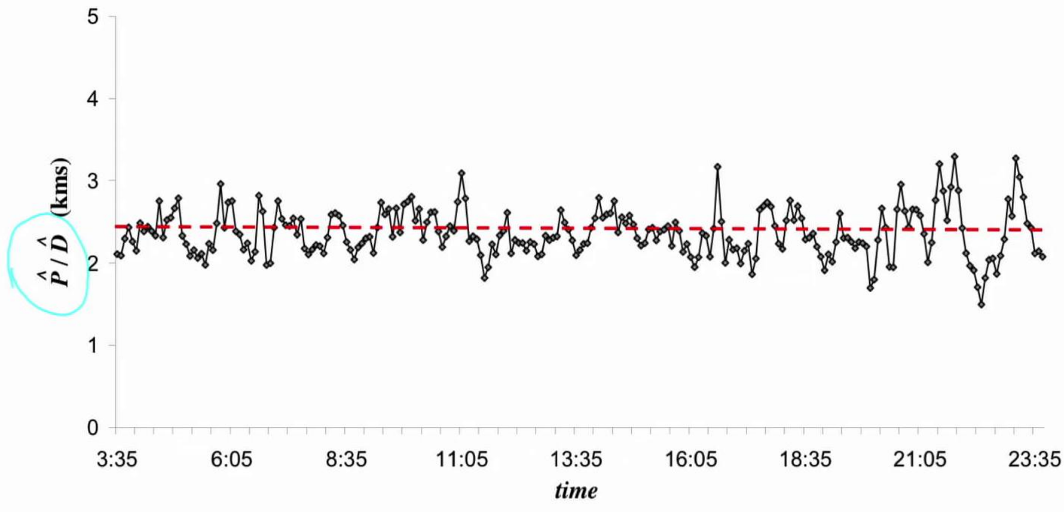
So now by combining the taxi detector data, we can see what is the relationship between the estimated number of vehicles and that other than speed of taxis. And what we see, we see that this points again, belong in the line with low scatter. And what we also see that during the morning and evening peak, we have a microscopic fundamental diagram that follows the same trend. And please observe there is a higher scatter over there where our sample size is small and our error in the estimation of accumulation is higher.

Notes

Summary

24m 33s

Taxi and detector data: Results



Let's now look at the ratio of production, the hat and output trip endings, the hat which are estimated based on the taxi and the detector data. So if we take this ratio during the course of the day, what we see is that this ratio fluctuates just a little bit around a value 2.3 kilometers. So this actually shows and conference a similar to finding as we also had in our simulations in San Francisco where the other average three blends of the vehicles is about constant with time. Please note that these might not be a universe law. So some further investigation is needed in other case studies to confirm it.

Notes

Summary

25m 15s

MFD - Summary

So summarizing the content of this video, we have been under simulation and under the umbilical evidence that the microscopic fundamental diagram exists for different networks with very low scatter and will have also have seen how it can be estimated by fusing data from different sources. So in the next video, we'll see under what conditions the sum of did with lower scatter exists for open networks. See you soon.

Notes

Summary

26m 09s