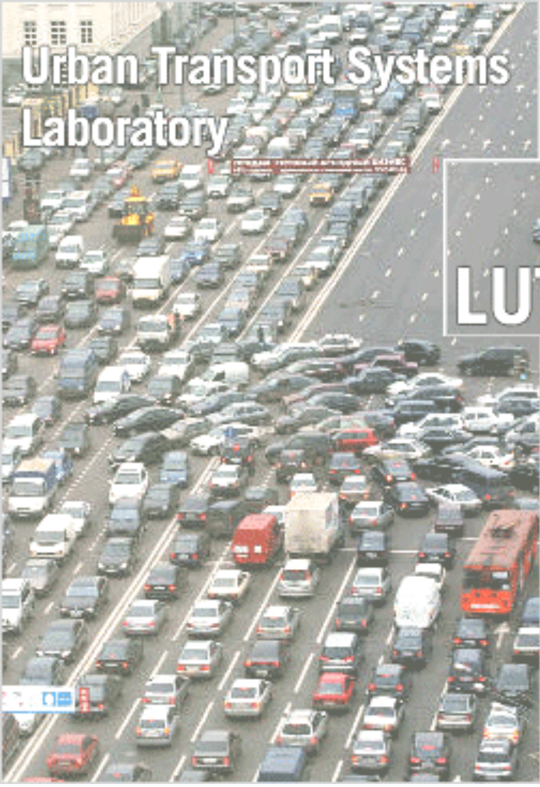


METAFERW: Mod**E**ling and con**T**rolling tr**AF**fic cong**E**stion in la**R**ge-scale urban multimodal net**W**orks

Prof. Nikolas Geroliminis

Urban Transport Systems Laboratory

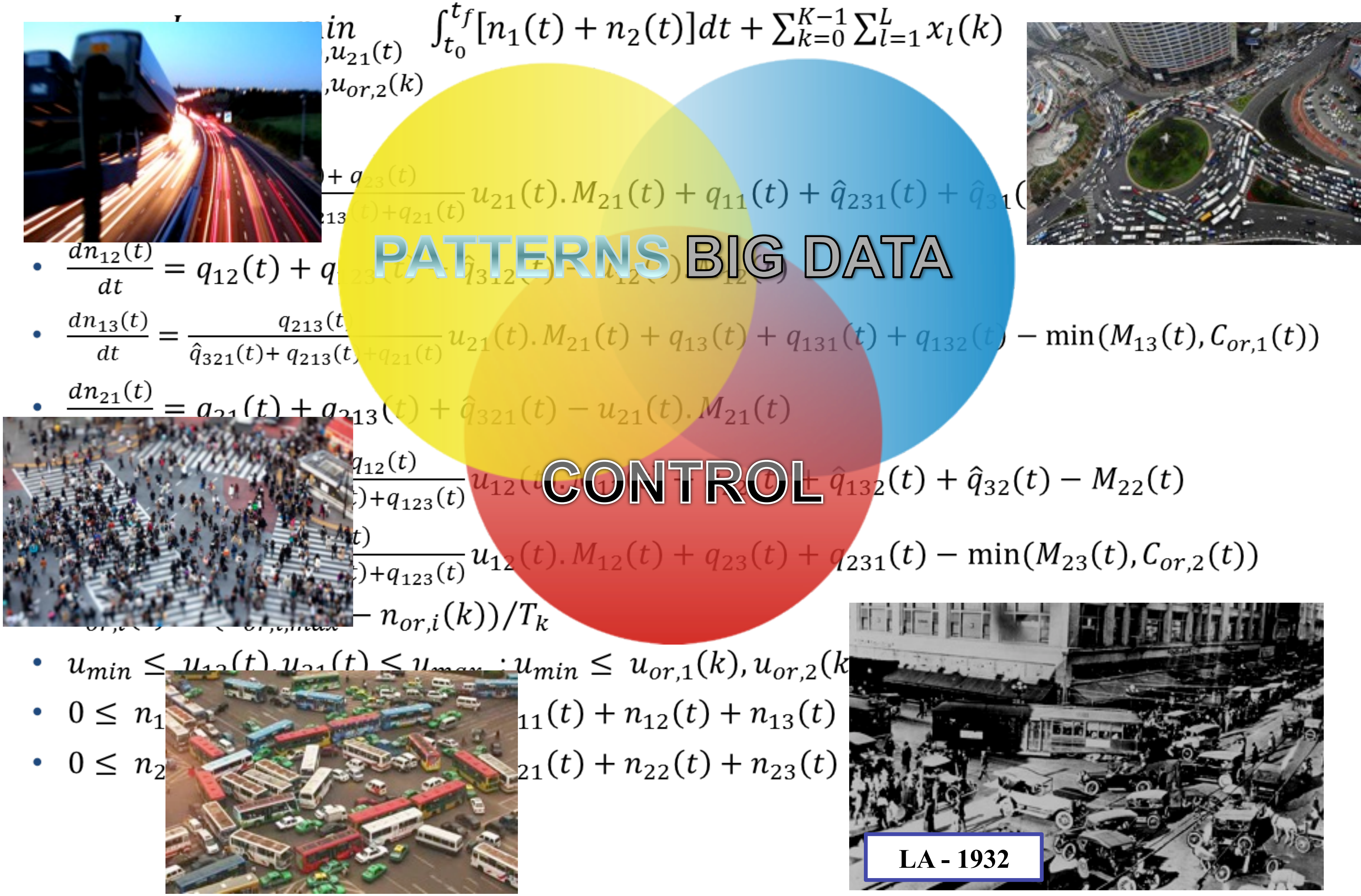
μεταφέρω = (Ancient Greek) transport or transfer
From μετά (“change in position”) + φέρω (“bear, carry”)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

ENAC School of Architecture, Civil and Environmental Engineering

Athens, Dec. 17th , 2014

A holistic approach of mobility



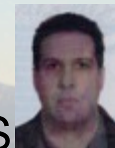
LUTS team

Nikolas Geroliminis

PostDocs

Jack Haddad (CE)

As of 5. 2013 Ass. Prof., Technion IS



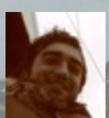
Kostas Aboudolas (EE)

As of 9. 2013 Lecturer, U of Glasgow, UK

Tasos Kouvelas (EE)

Wei Liu (CE)

PhD Students



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As of 3. 2014 Lecturer, U Lancaster, UK

Yuxuan Ji (CS)

As of 8.2014, Bloomberg, CH

Mohsen Ramezani (EE)

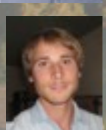
PhD Defense 10.2014

Nan Zheng (CE)

PhD Defense 11.2014

Reza Saeedmanesh (EE)

Mikhail Murashkin (Physics)



Raphael Lamotte (CE)

Mehmet Yildirimoglu (CE)

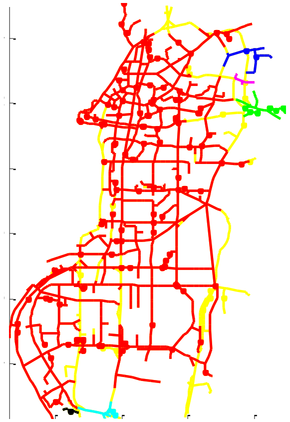
Challenges of City Traffic -Complex Systems

Non-linear interactions

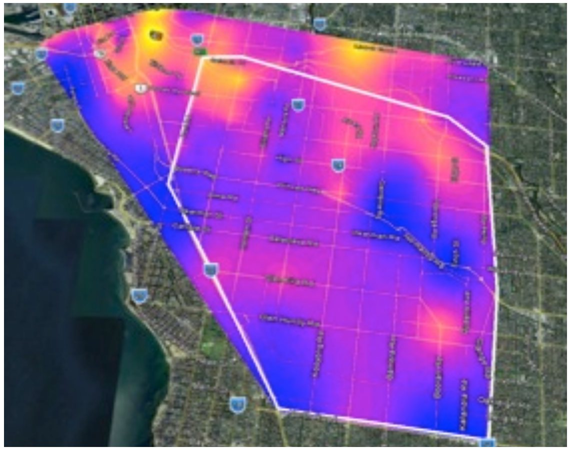
- Components influence the system and vice versa
- Components adapt
- Spreading phenomena

Limits to predictability

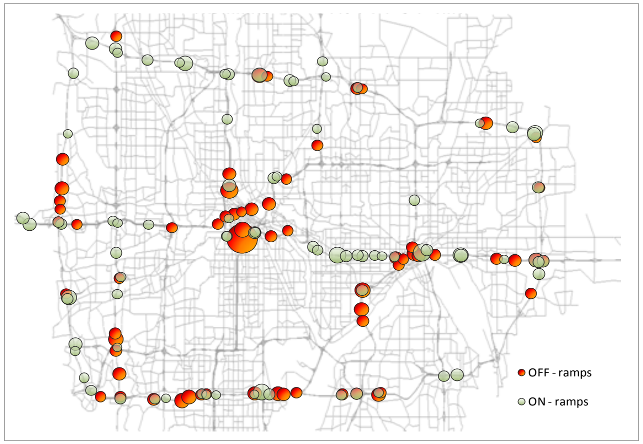
Limits to control



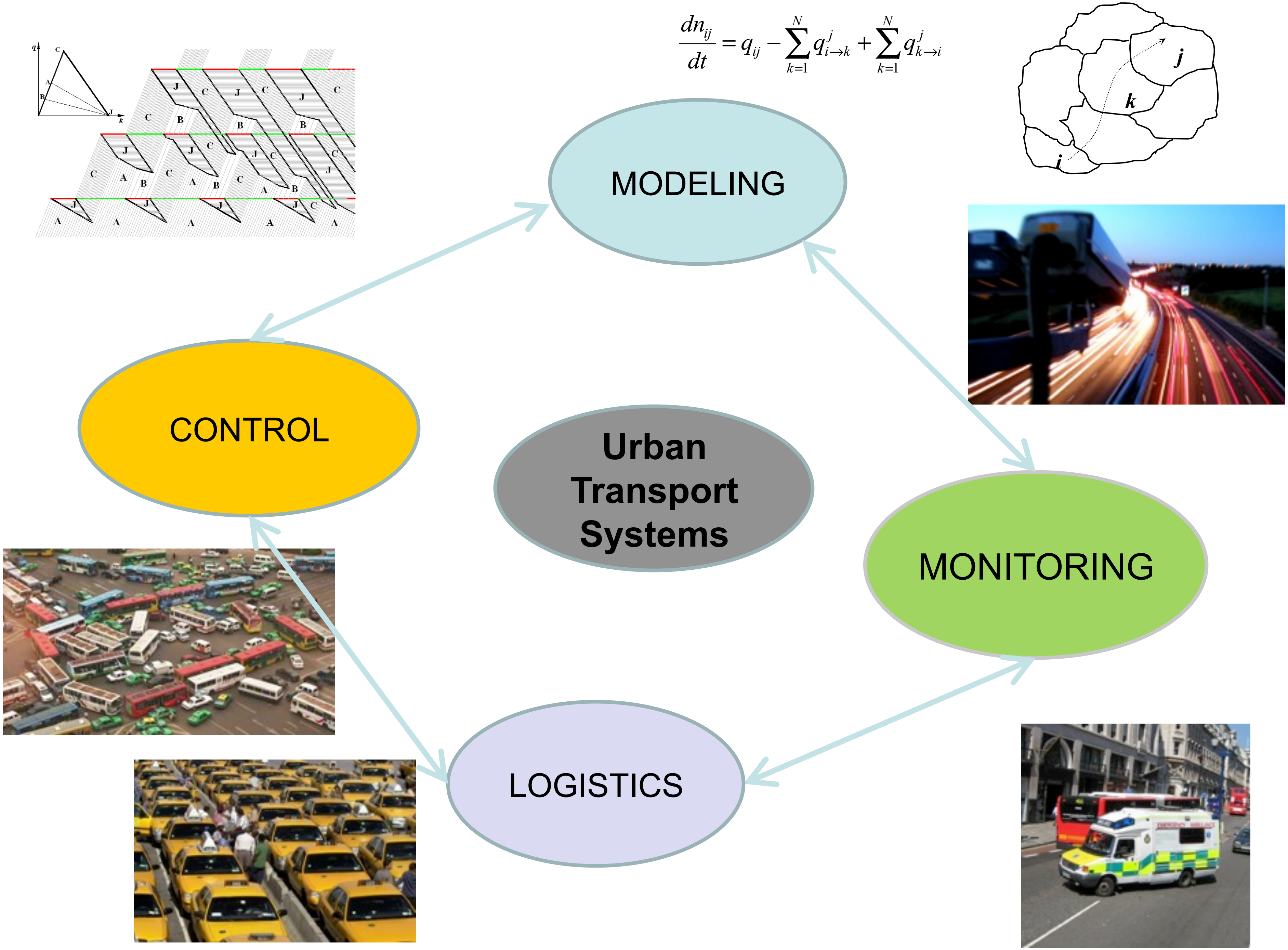
Shenzhen, China



Melbourne, AUS



Minneapolis, USA



$\frac{dn_{ij}}{dt} = q_{ij} - \sum_{k=1}^{N} q_{i\to k}^{j} + \sum_{k=1}^{N} q_{k\to i}^{j}$
i
j
k
MODELING
CONTROL
Urban Transport Systems
MONITORING
LOGISTICS

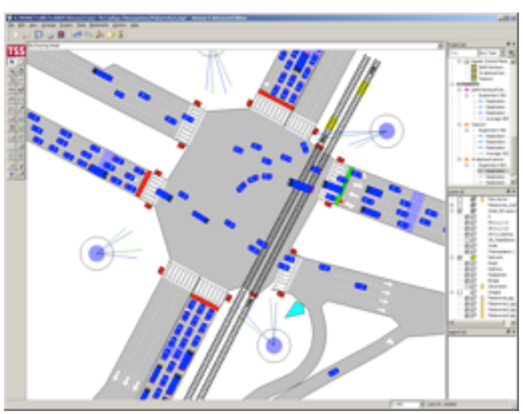
State-of-the-art: Granularity of traffic models

Fine-grained

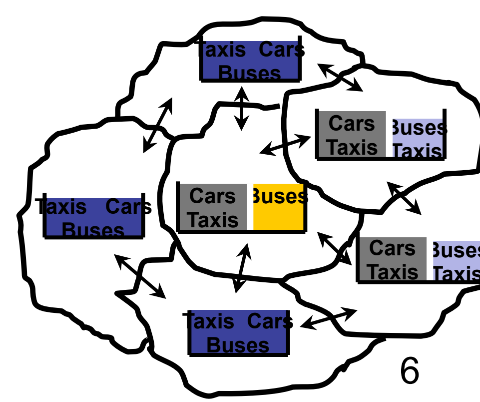
- Data intensive
- Questionable calibration
- Expensive computation
- Unreliable prediction
- Fragmented optimization

Coarse-grained

- Less accurate
- Lack dynamics
- Non-physical
- Planning oriented



traffic modeling



State-of-the-art: Traffic optimization & control

Most optimization methods for transport networks

- Fragmented and uncoordinated
- Suited for toy networks with simplified dynamics
- Apply decentralized control
- Micro-simulation and scenario analysis

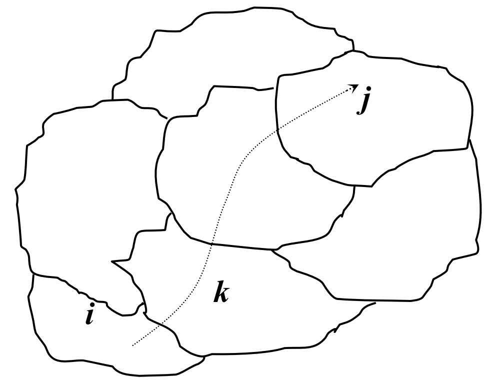
Cairo

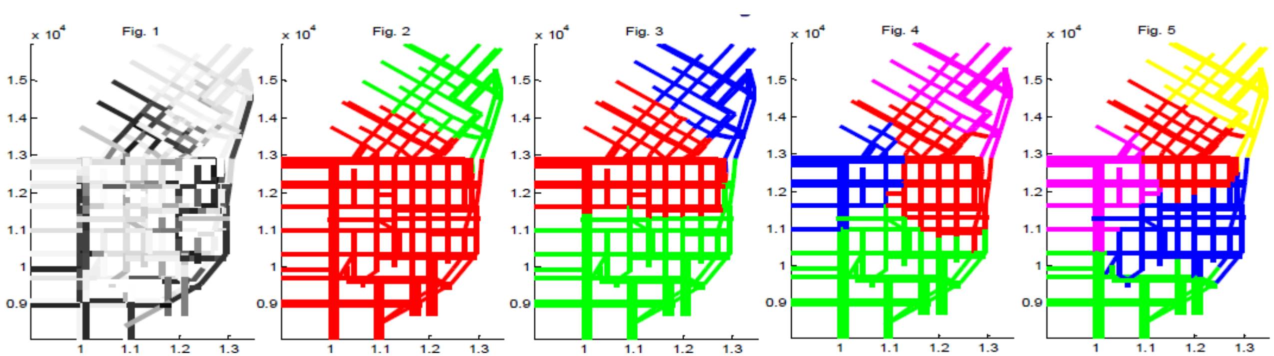
Bangkok

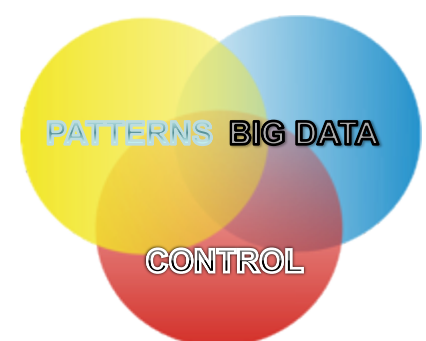
Paris

A holistic approach for smart traffic in cities

- Physical Patterns in aggregated models
- Partitioning (static, dynamic)
- Hierarchical control
- Multimodality







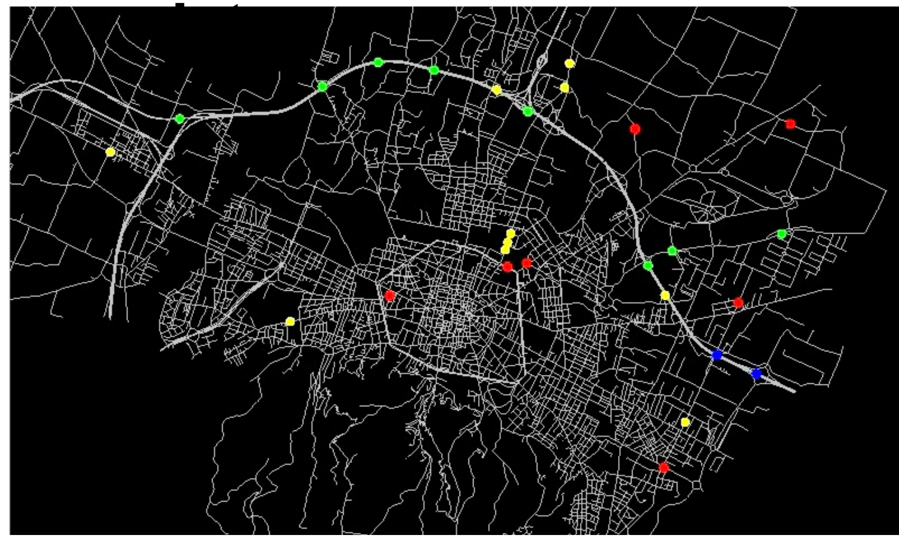
AGGREGATE BEHAVIOR
= ?
SCALED UP VERSION OF LINK BEHAVIOR

MONITORING

Heterogeneity

- Spatial and Temporal
- Congestion Level
- Topology
- Modes of transport
- Sensing equipment

Sparse multi-sensor



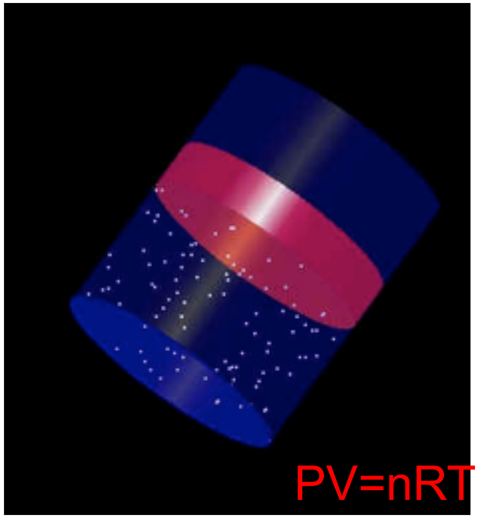
Develop travel time field and route choice information

Pictures provided by Armando Bazzani (Un. of Bologna)

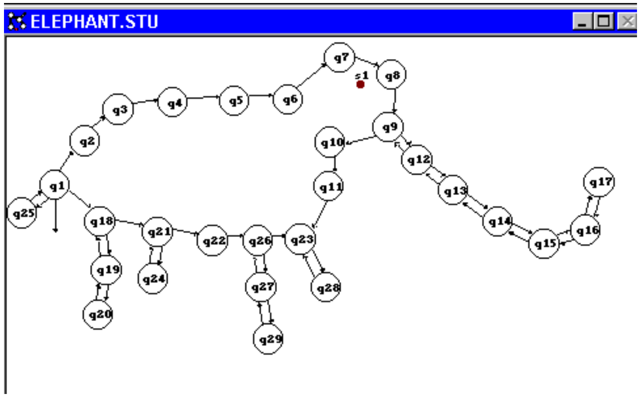
The promise of aggregate models

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

PROPOSE→ MONITOR→MODIFY



- Information Technology



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

WHY MACRO?

- Humans make choices in terms of routes, destinations and driving behavior (unpredictability)
- Not a clear distinction between free-flow and congested traffic states. Empirical analysis of spatio-temporal congestion patterns has revealed additional complexity of traffic states (e.g. Helbing's group work)
- Need for real-time hierarchical traffic management schemes (decentralized control might not work for heavily congested systems)

- Urban regions approximately exhibit a "Macroscopic Fundamental Diagram"(MFD) relating the number of vehicles to space-mean speed (or flow)
- Robust linear relation between the region's average flow and its total outflow (rate vehicles reach their destinations)
- MFD is a property of the network infrastructure and control and not of the demand (time-dependent origin-destination tables are difficult).

Macroscopic modeling of traffic in congested cities

A Macroscopic Fundamental Diagram (MFD) for city traffic

Existence (Simulation evidence)

Existence (Empirical observations)

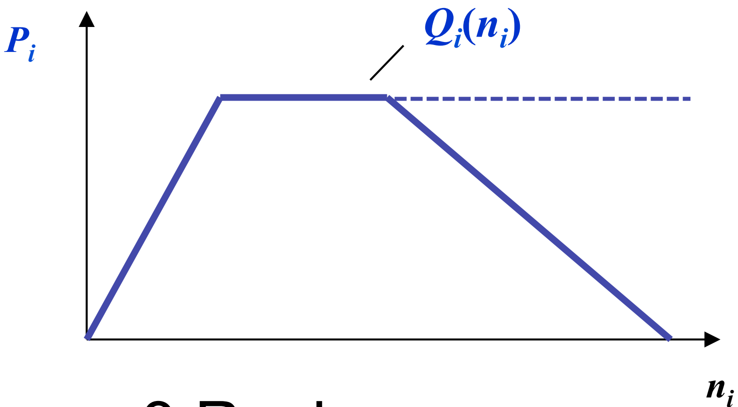
Description of dynamics

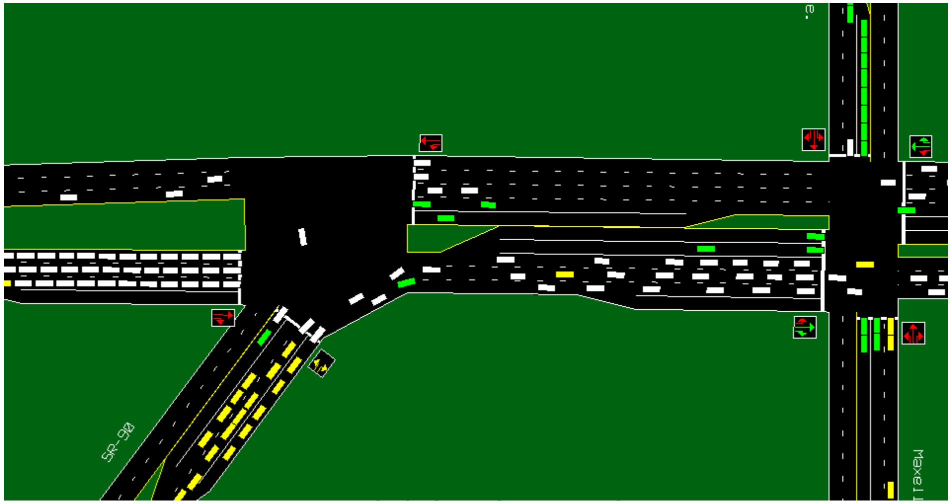
Multimodal networks

Perimeter control

Fundamental Diagram (FD) for a link *i*

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





- 3 Regimes

I : Undersaturated

II : Efficient

III : Oversaturated

Growing queues from the downstream link block the arrivals

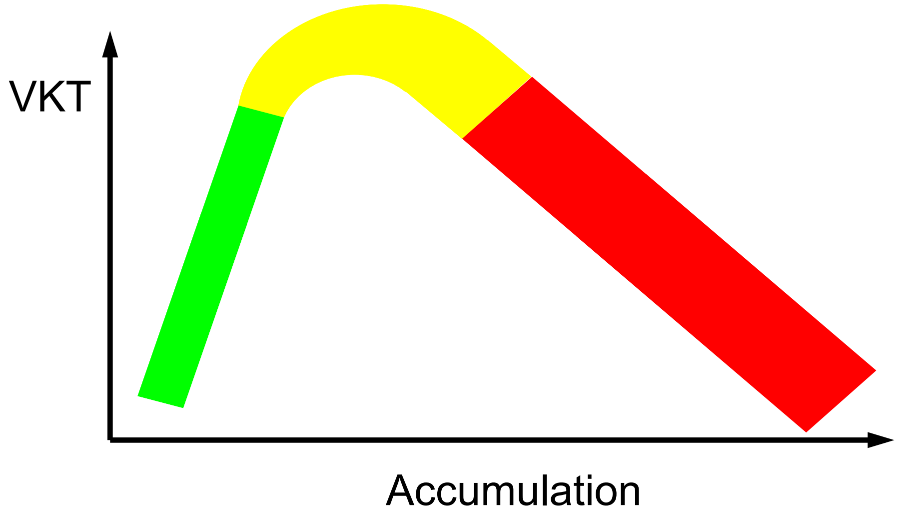
Theory: Generalization to networks

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

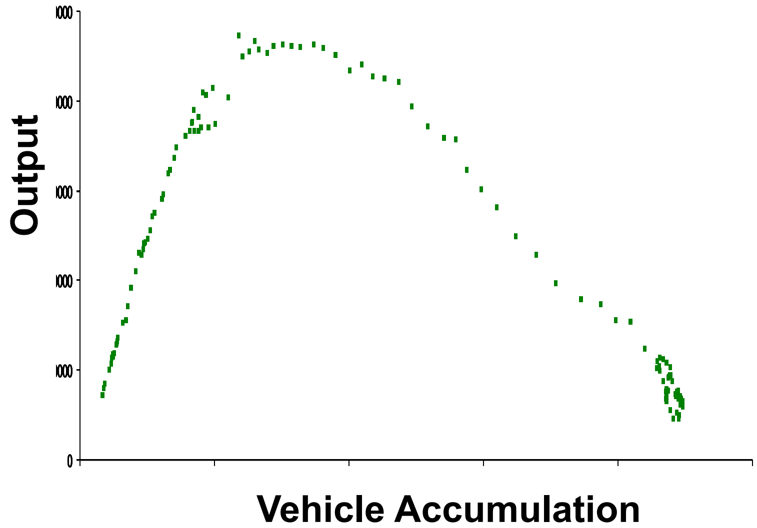
AGGREGATE BEHAVIOR

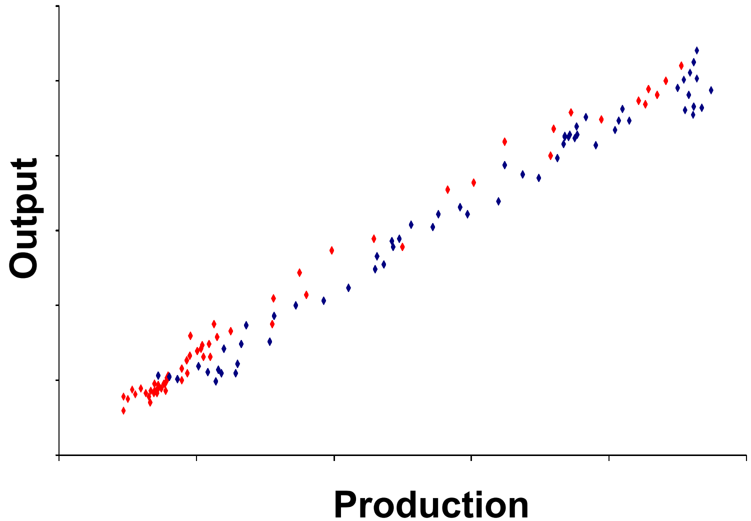
=

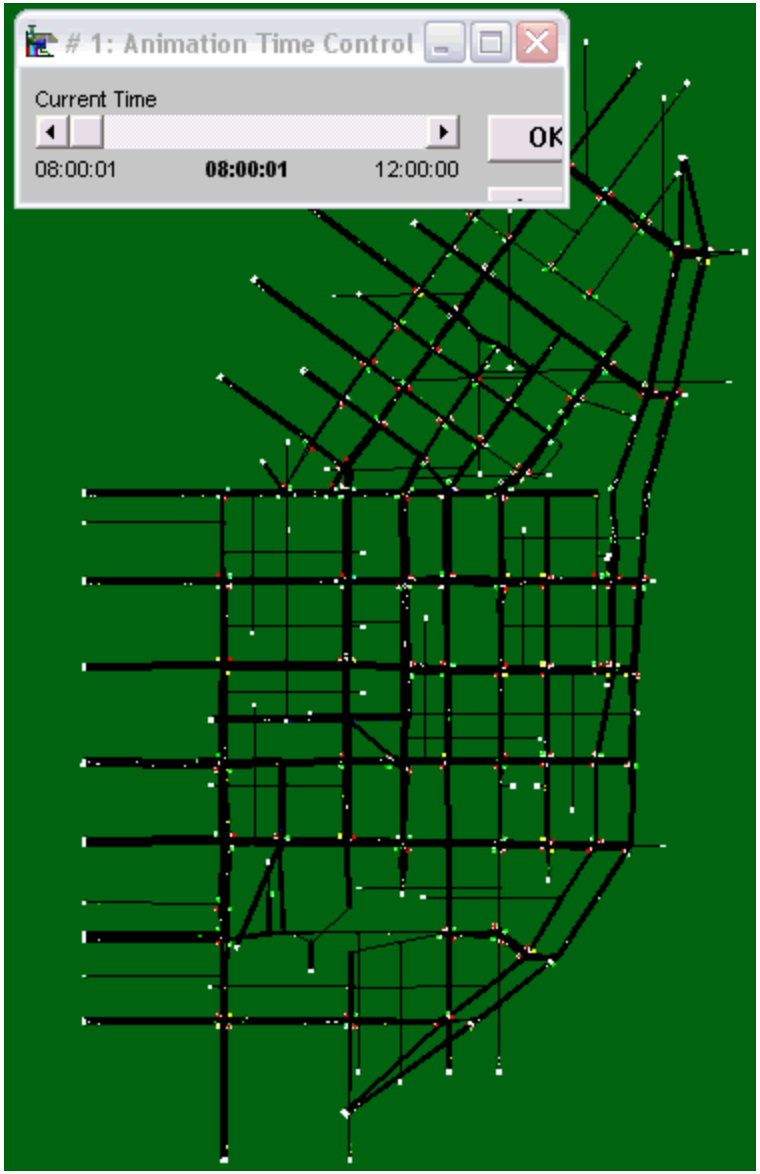
SCALED UP VERSION OF LINK BEHAVIOR



Macroscopic Fundamental Diagram (MFD)

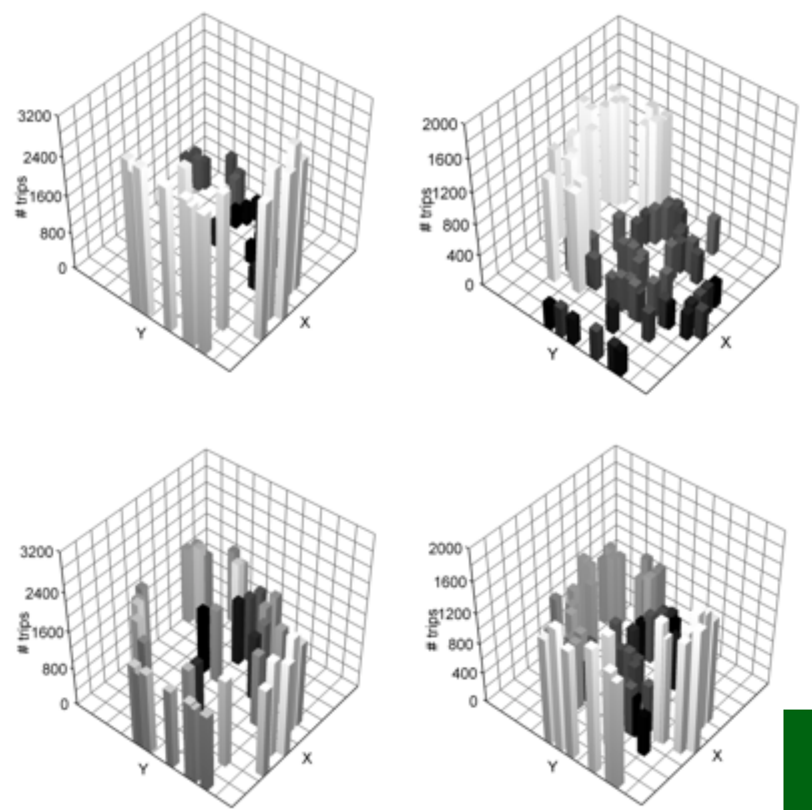


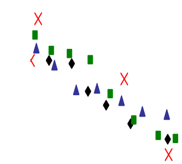




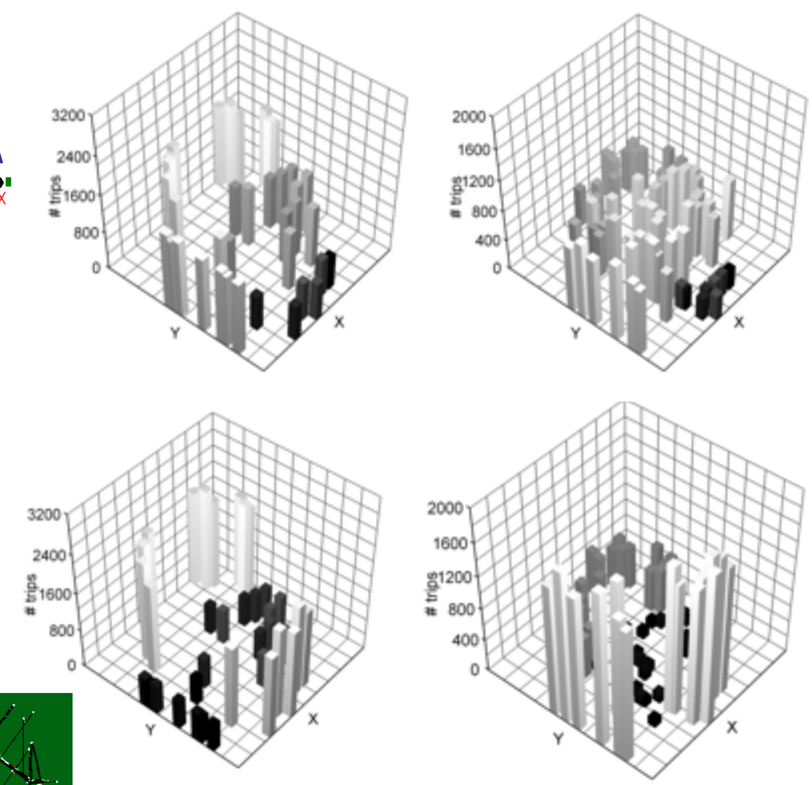
MFD – Sensitivity to Demand

DESTINATIONS PER NODE | **ORIGINS PER NODE**



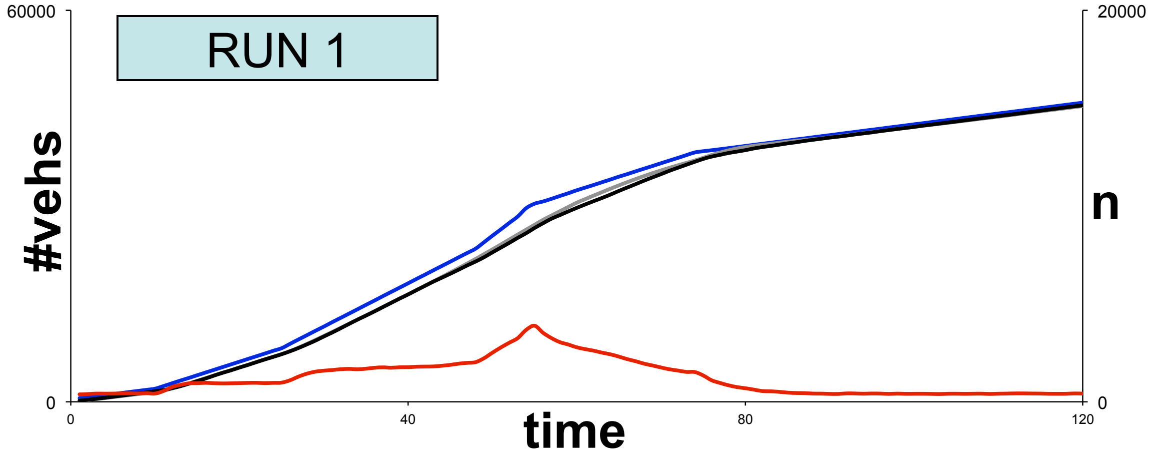


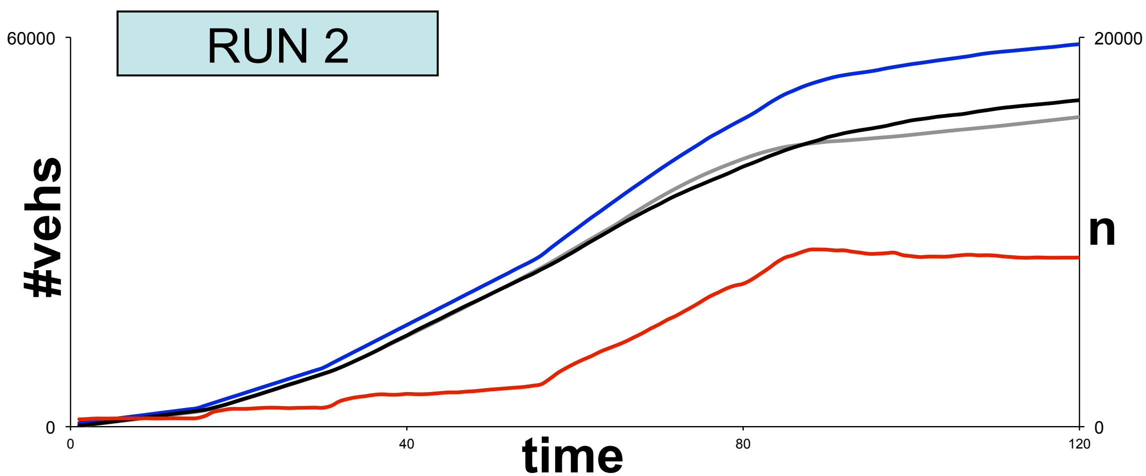
DESTINATIONS PER NODE | **ORIGINS PER NODE**



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

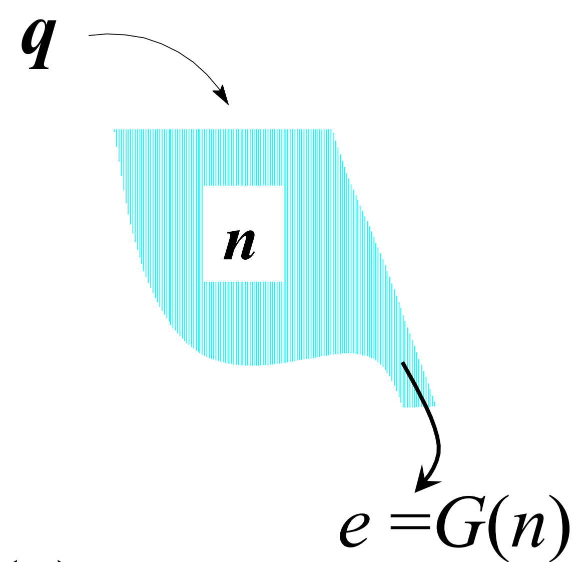
MFD - Dynamics

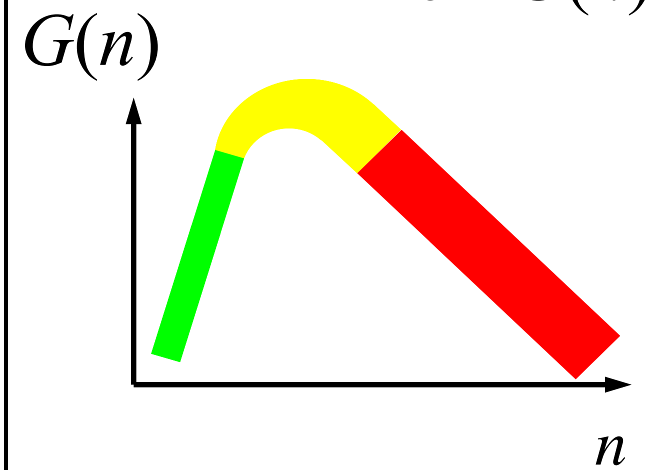




INPUT **OUTPUT** **ESTIMATED OUTPUT** **ACCUMULATION**

Geroliminis and Daganzo, 2007

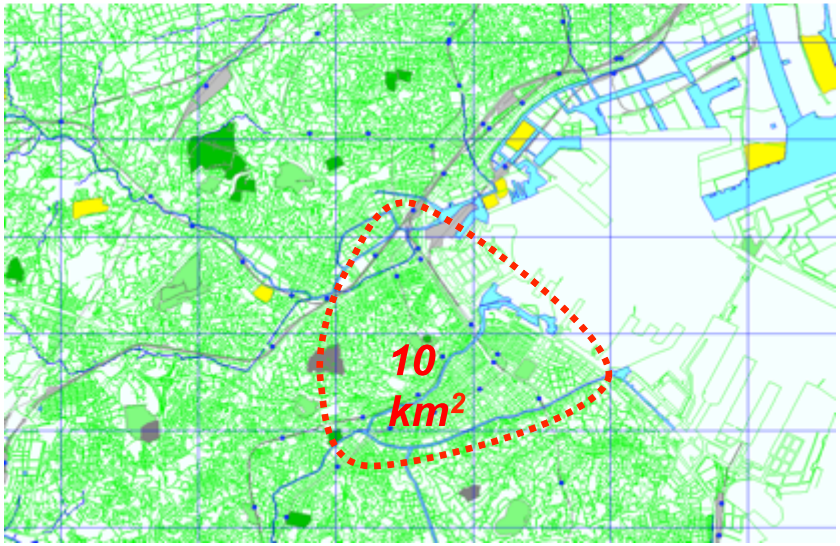


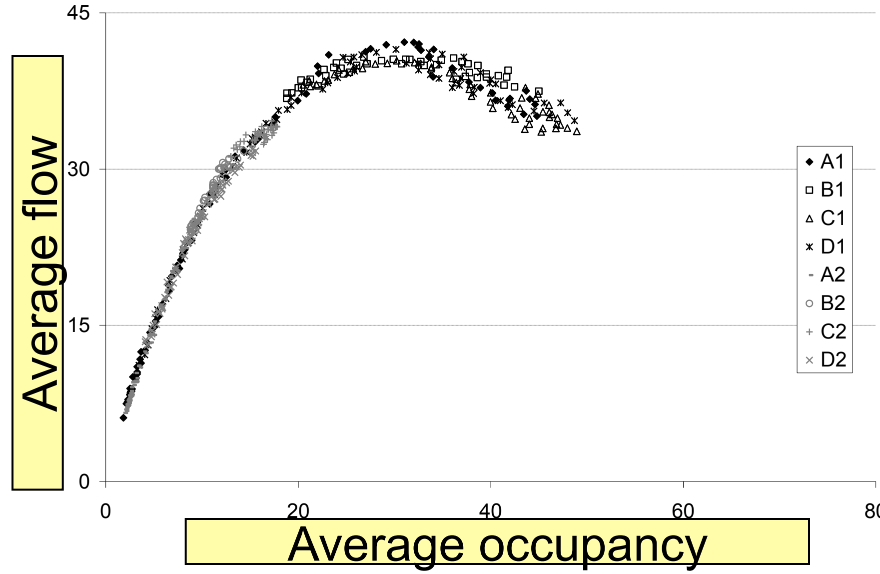


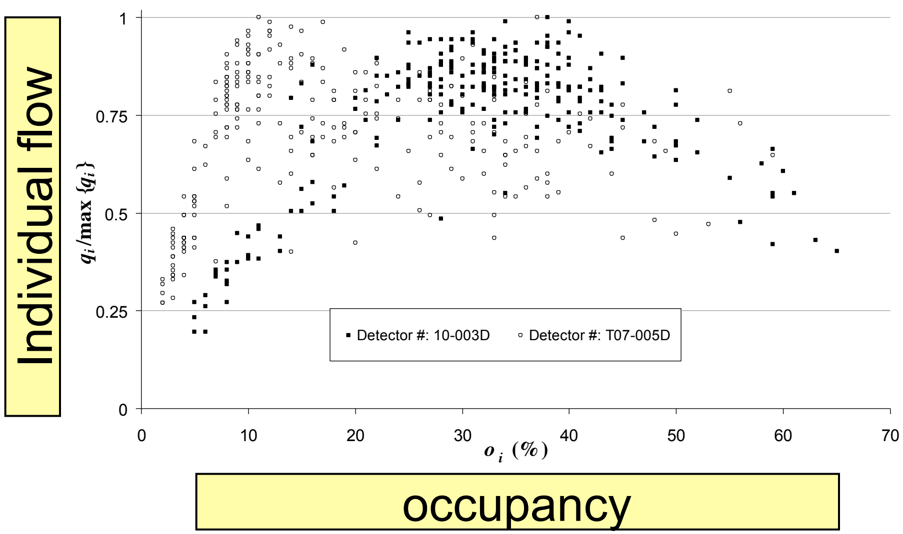
$$\frac{dn(t)}{dt} = q(t) - G(n(t))$$

Daganzo, 2007

MFD Empirical results







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

Geroliminis and Daganzo (2008) – Tr. Res. Part B

Fusing taxi and detector data

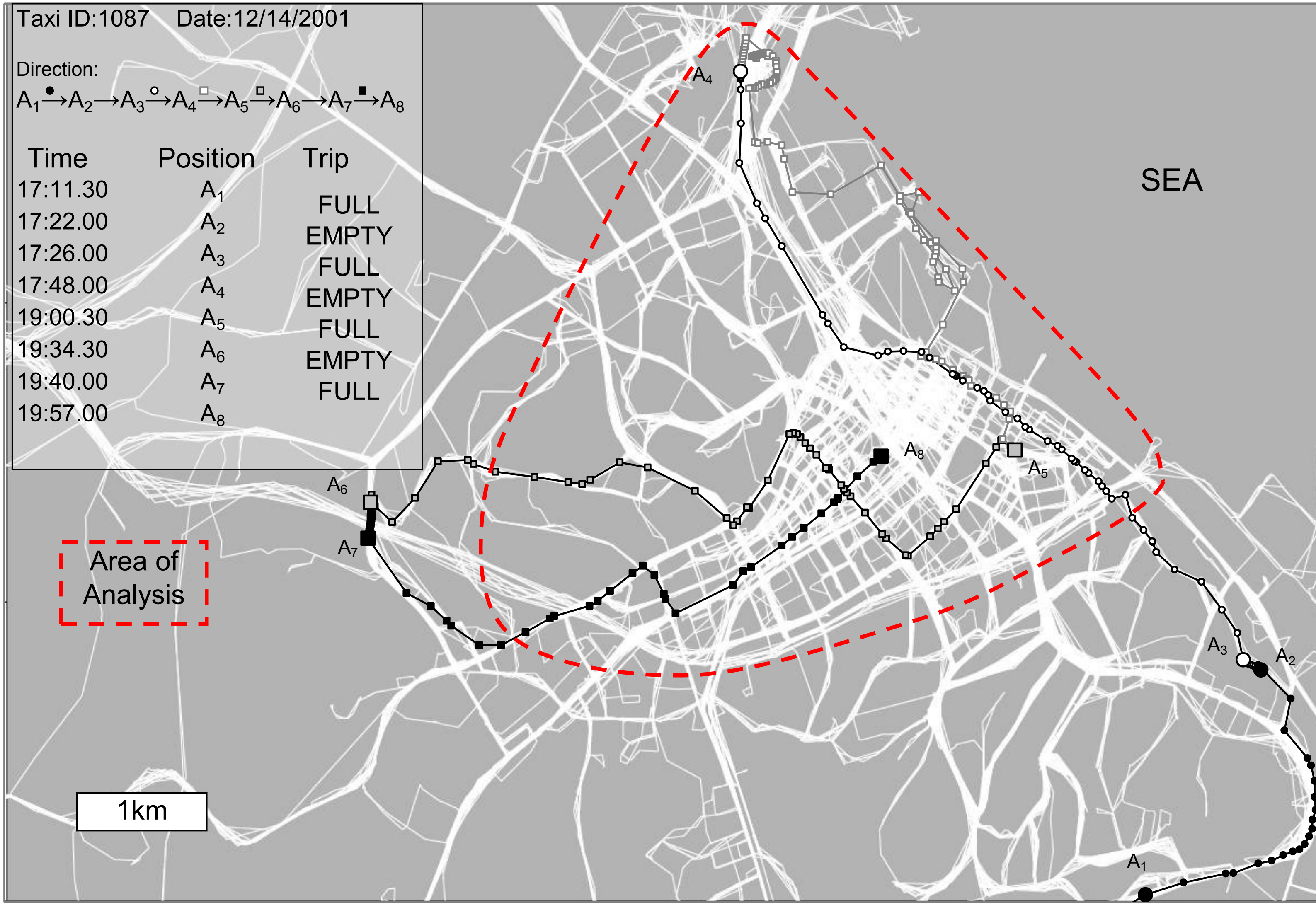
An MFD exists on the part of the network covered by detectors. What about the whole network?

1. Filter for passenger-carrying taxis (i.e. full)

2. Estimation of accumulation and speed

3. Results

Illustration of Filter Results



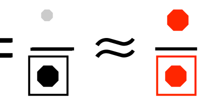
Estimation of accumulation and speed

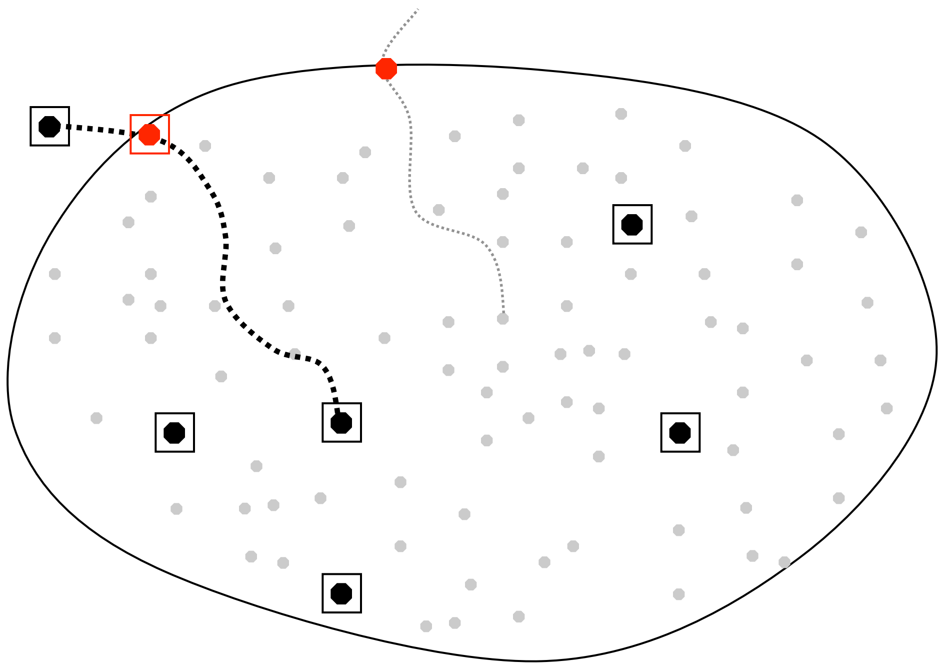
Conjecture: Passenger carrying taxis use the same parts of the network as cars

Then:

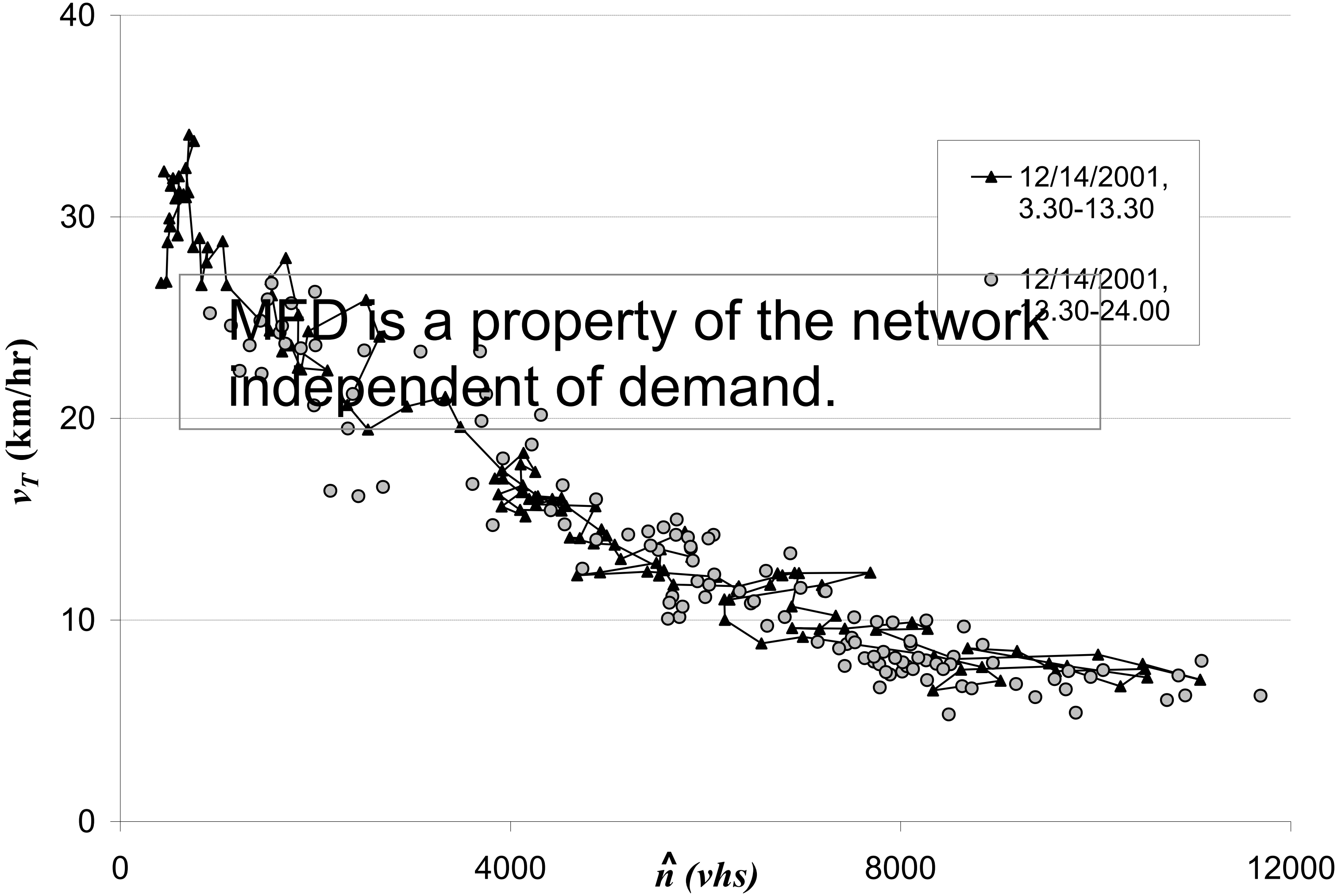
$$u(t) \approx \bar{u}_{taxi}(t)$$

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

$\Phi(t) =$ 



Real World Experiment: Results



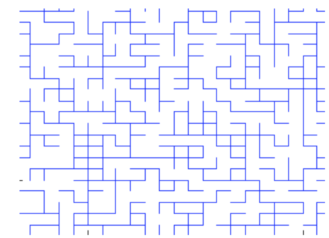
MFD is a property of the network independent of demand.

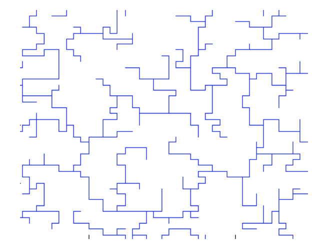
Network type and MFD

MFD **IS NOT** A UNIVERSAL LAW

Regularity conditions that possibly ensure an MFD

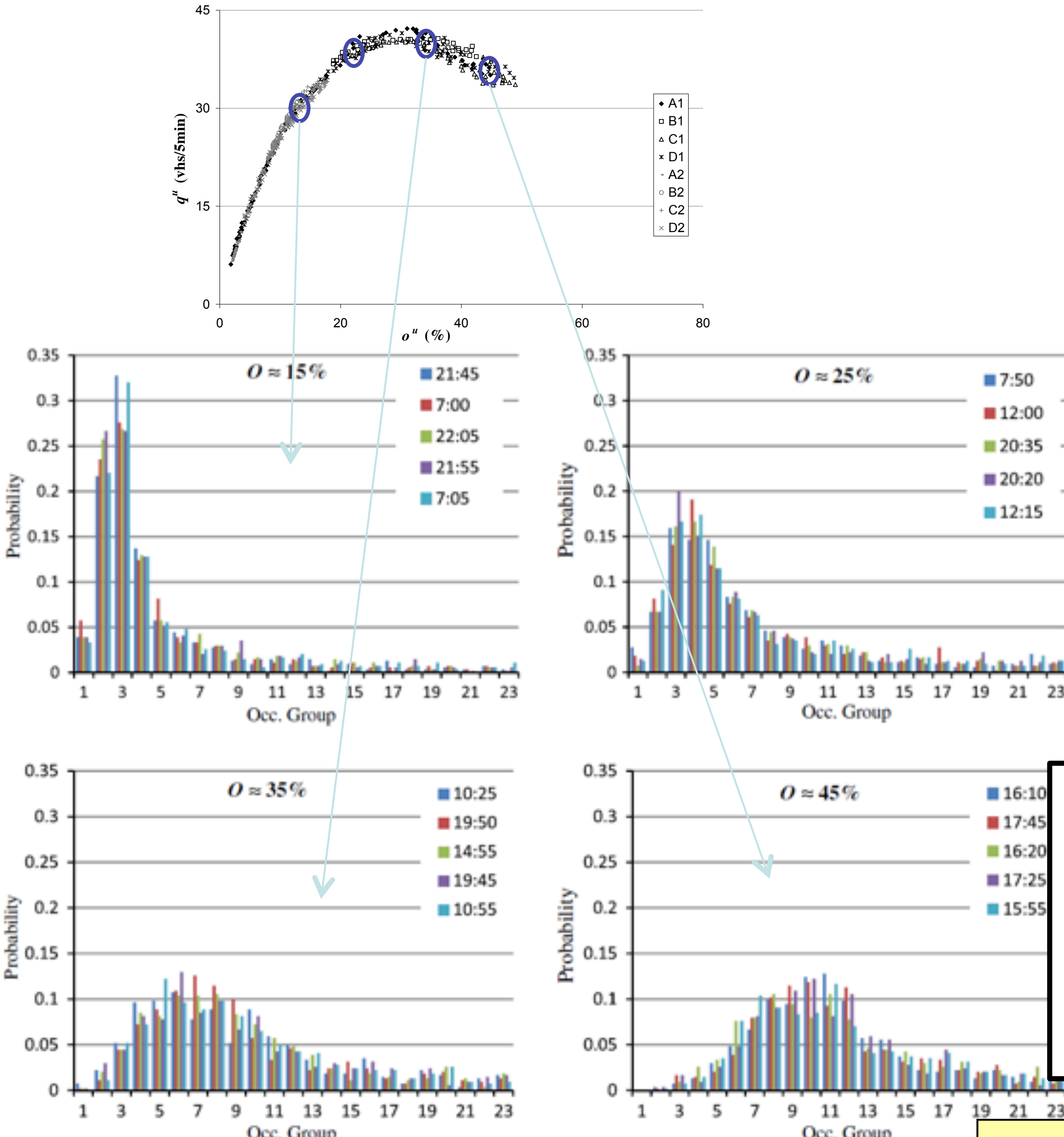
- A slow-varying and distributed demand
- Homogeneous spatial distribution of congestion
- A redundant network with many route choices
- Homogeneity in network topology





- An MFD with low scatter
  - locally heterogeneous but macroscopically regular networks (e.g. cities with multiple modes)
- An MFD with high scatter
  - Networks with uneven and inconsistent distribution of congestion (e.g. freeways)

Properties of a well-defined MFD



$d_r(t)$: pdf of individual detectors' density in region r
$Q(t)$ and $O(t)$: Average network flow and density

$$\{Q(t_1) = Q(t_2) \quad \text{and} \quad O(t_1) = O(t_2)\}$$

$$\Longleftrightarrow d_r(t_1) \sim d_r(t_2).$$

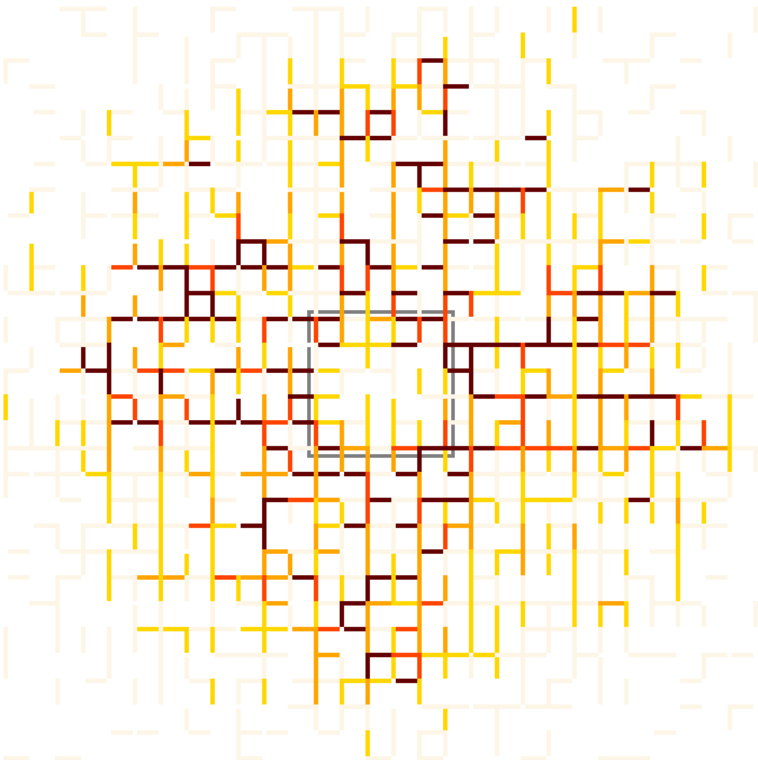
Variance much higher than binomial's

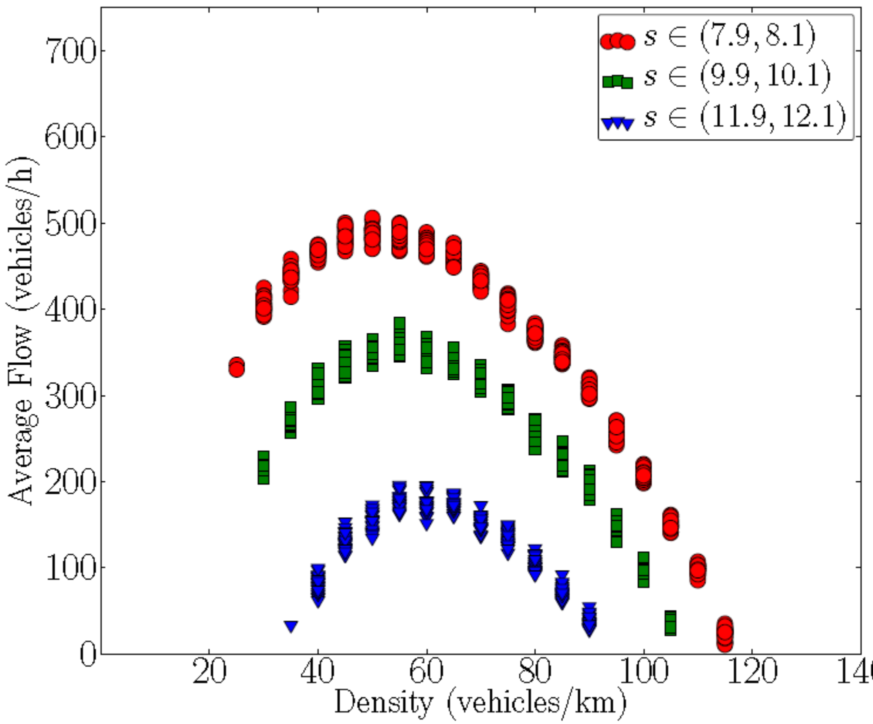
WHY?

Correlation of link density (propagation)

Geroliminis and Sun (2011) – Tr. Res. Part B

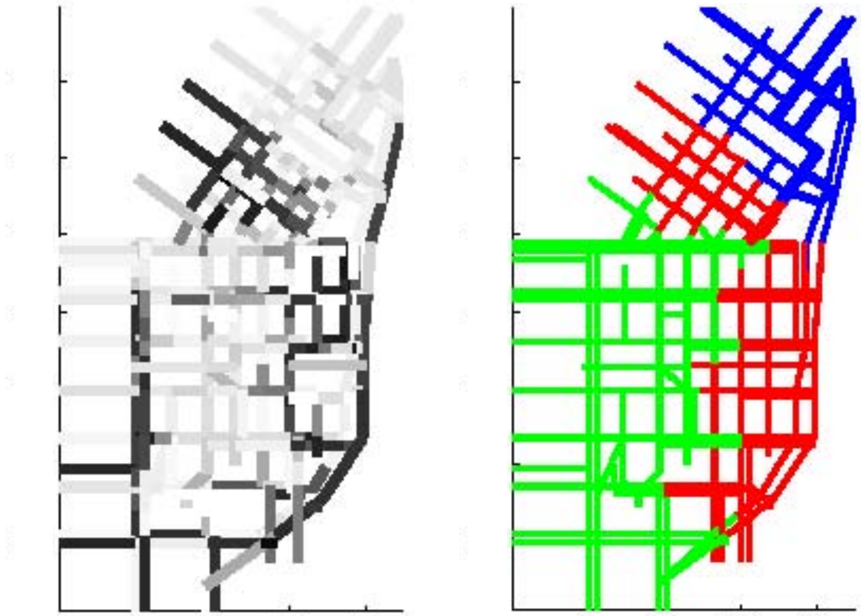
Spatial Variability and Network Capacity

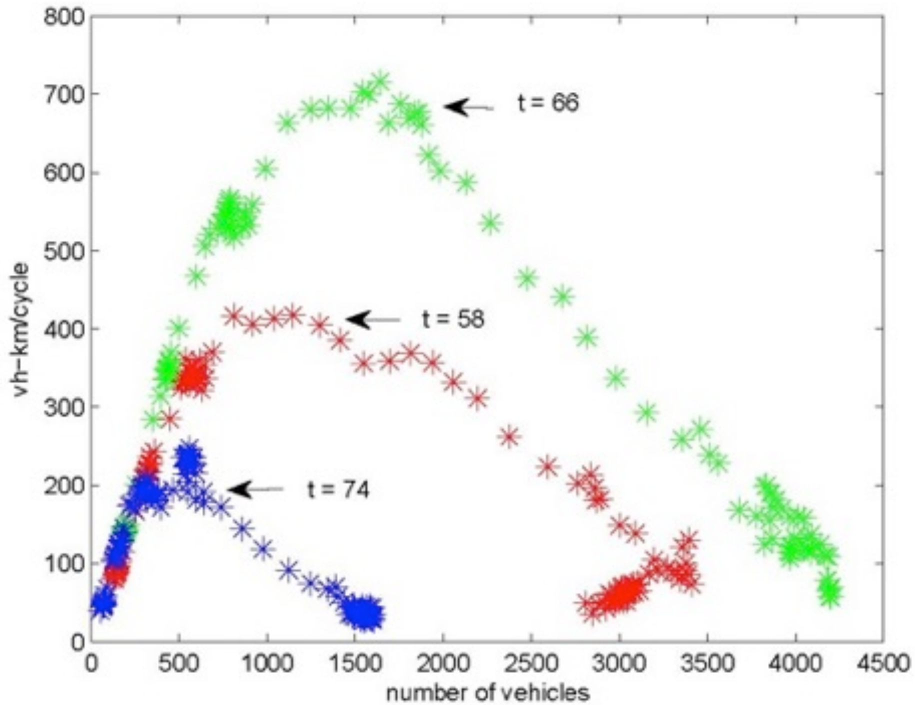




Mazloumian, Geroliminis and Helbing (2010) – Ph.Trans.Roy. Soc. A

Clustering – Congestion Dynamics



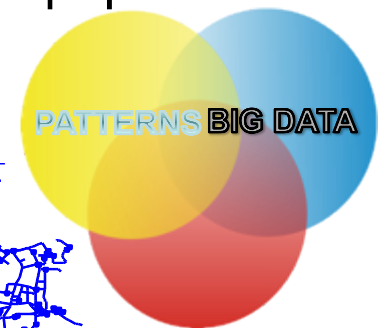


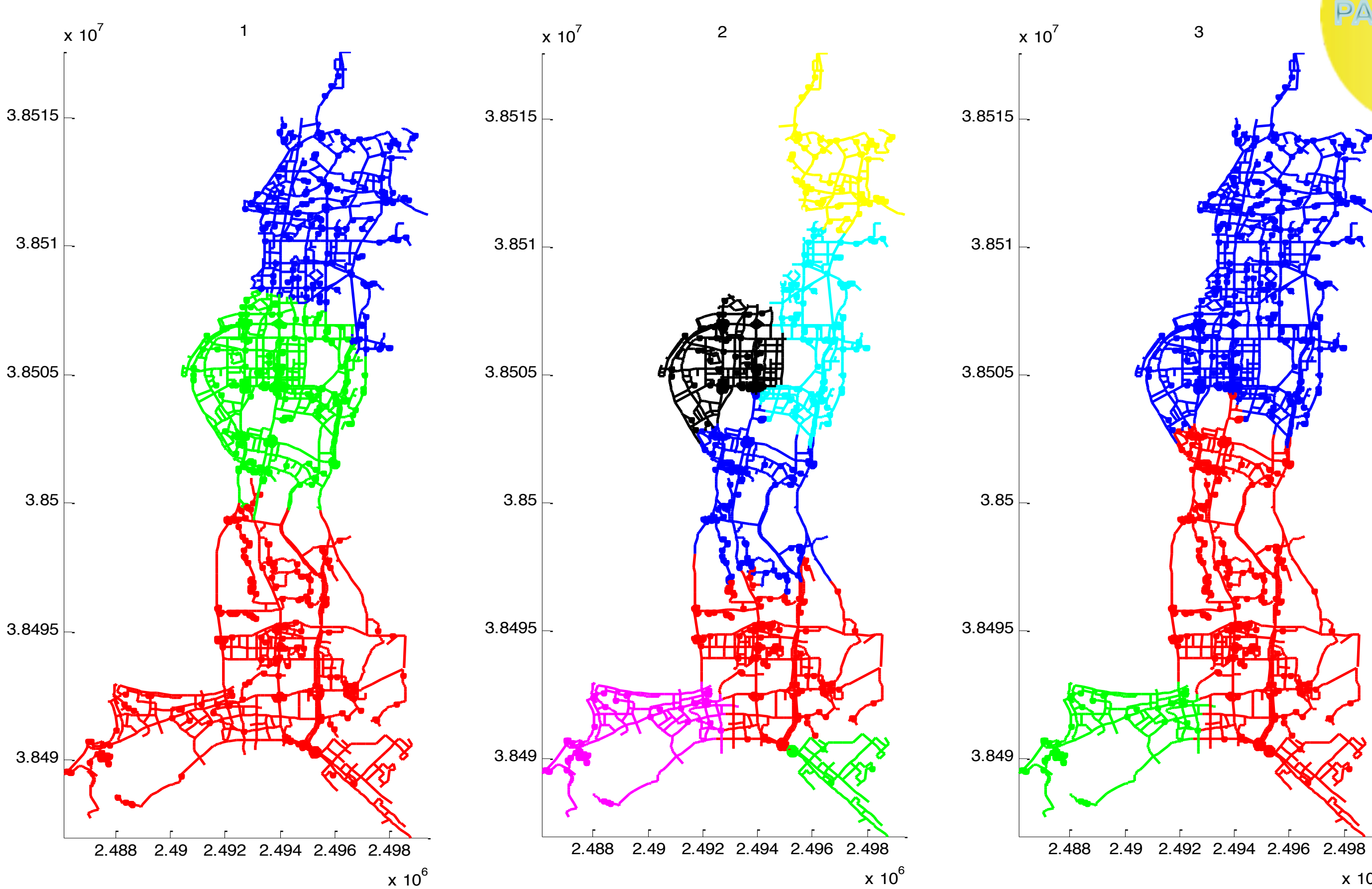
Clusters of a city reach congestion at different times

Ji and Geroliminis (2012) – Trans. Res. Part B

Dynamic Congestion Patterns

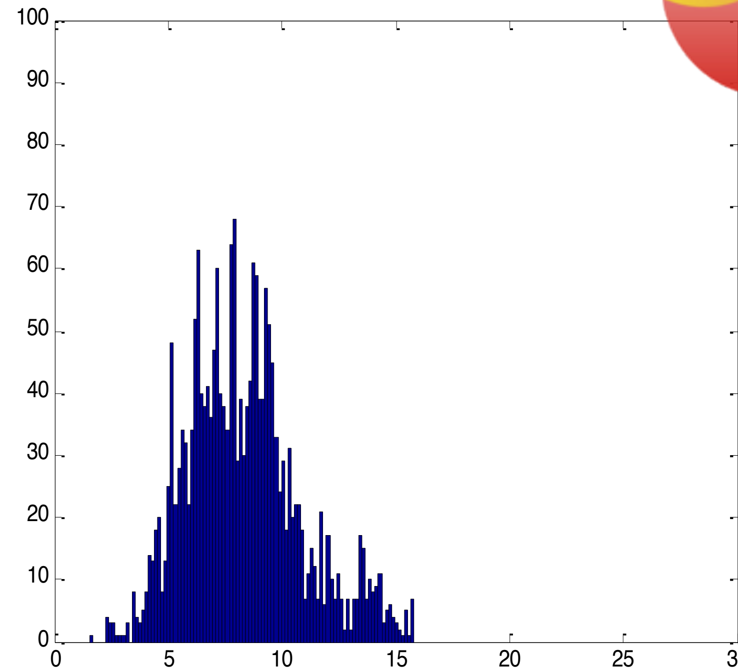
20000 taxis (50M points/day) 9000 links Shenzhen 12M population





Ji and Geroliminis (2014) – TRR

Speed profile evolution



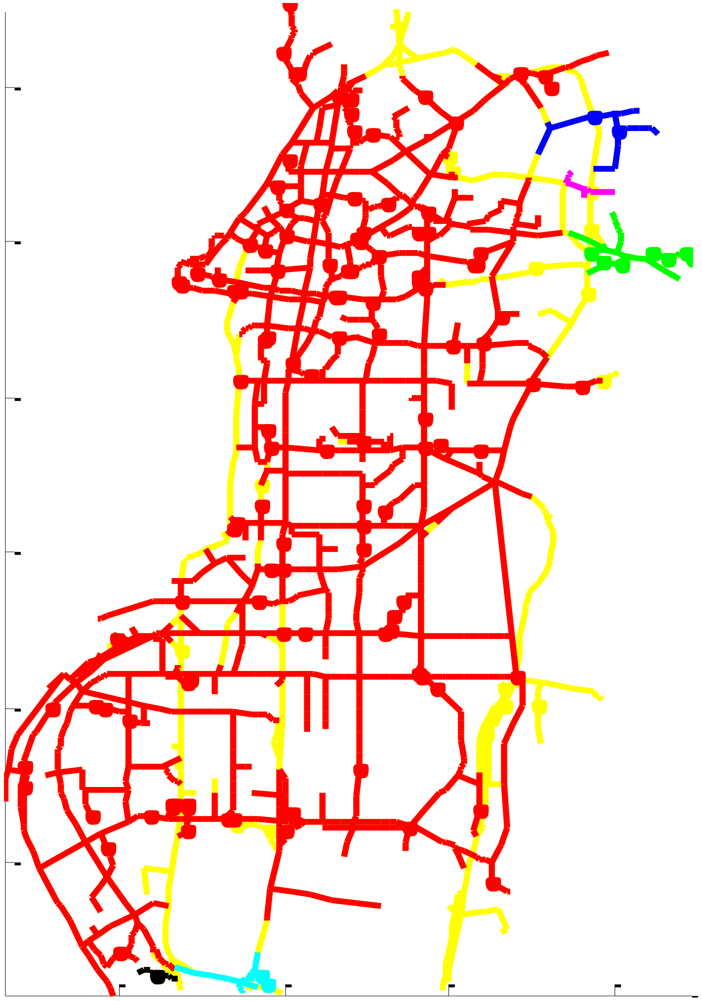
Link Speed Histogram (m/sec)

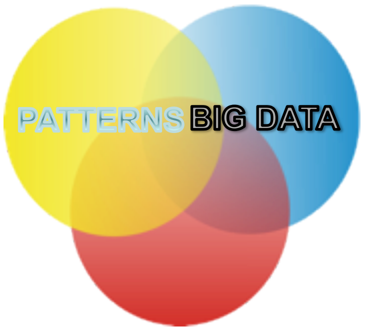
- Estimate link speeds from taxi data
- Identify congested links over time
- Spatial smoothing
- Estimate the largest connected components

Congestion Propagation

Small number of critical pockets of congestion

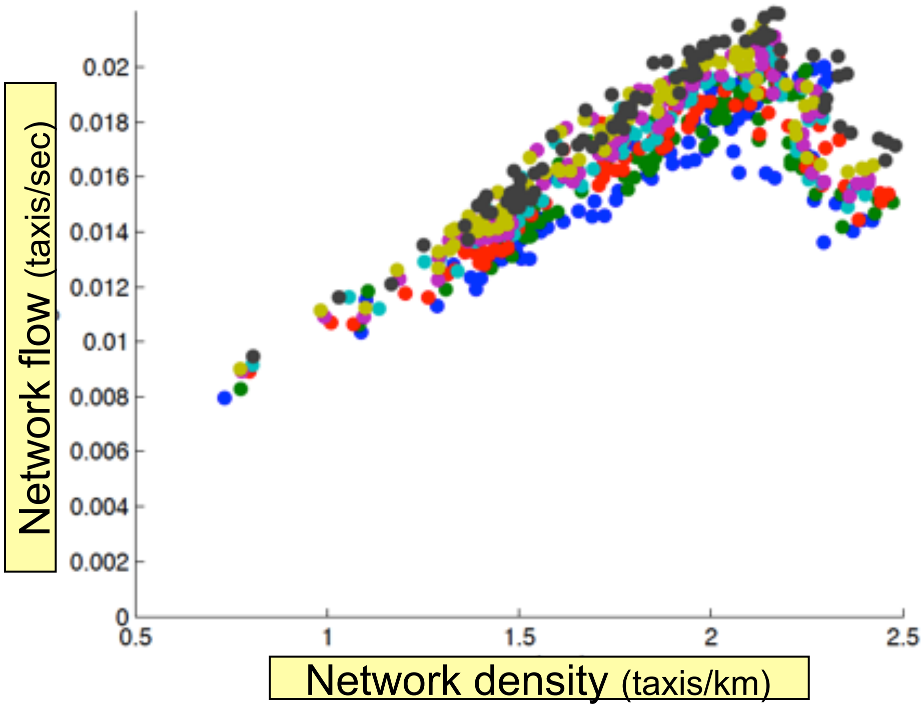
Significant Spatial correlations





Aggregated patterns

PATTERNS BIG DATA



$$n_j = n_u \times (l_j / l_u) \times \left(\left(n_j^f \middle/ n_j^e \right) \middle/ \left(n_u^f / n_u^e \right) \right)$$

number of taxis is proportional

- to the size of the region
- to the ratio of full over empty taxis

Multimodal networks

- In urban networks, buses usually share the same network with the other vehicles.
- Movement Conflicts in multi-modal urban traffic systems: Modeling Congestion and developing more sustainable cities
- Increasing bus frequency decreases the flow of vehicles but can increase the flow of passengers.

- **Competing modes**
- **Parking**
- **Pax vs. veh throughput**

MULTIMODAL CITIES

Performance Measures

Vehicle Hours Traveled
Vehicle Kilometers Traveled

Passenger Hours Traveled
Passenger Kilometers Traveled

→

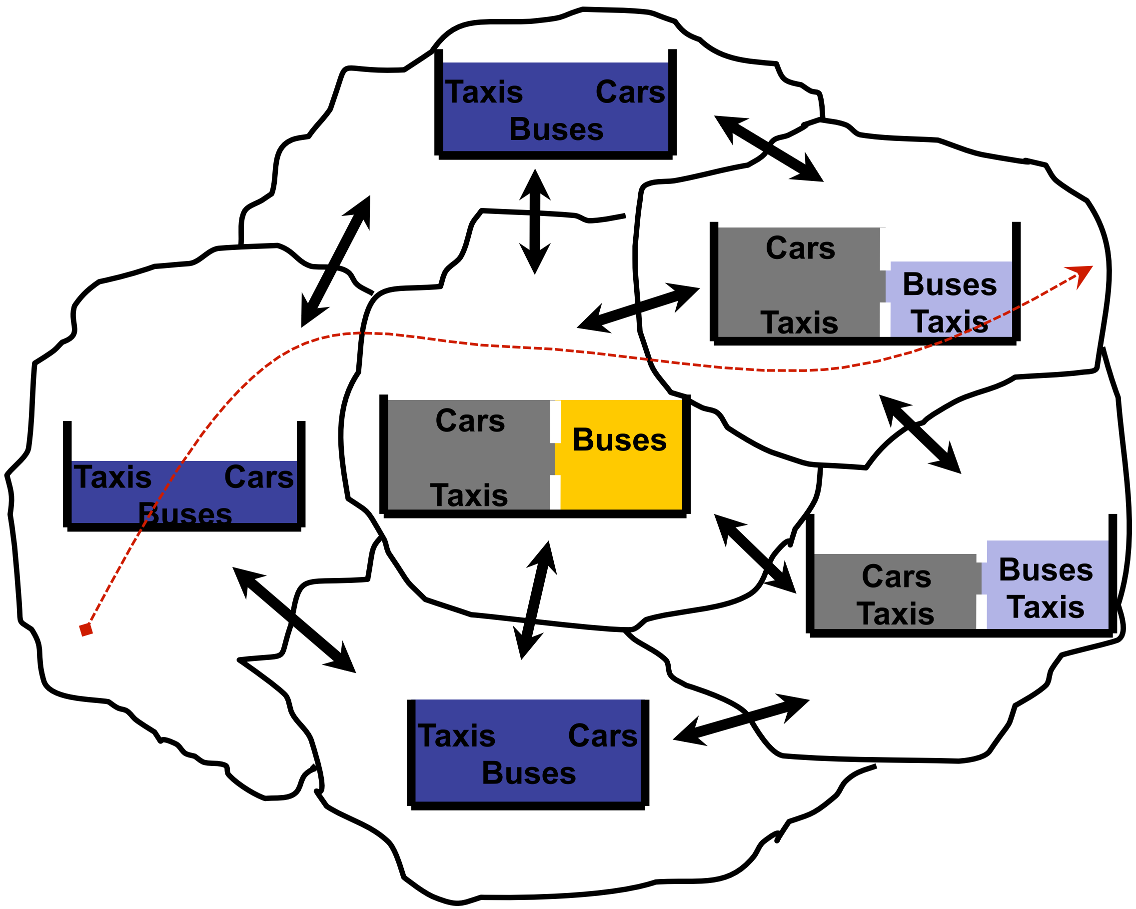
Mobility (Accessibility)

Emissions (Environ. Impacts)

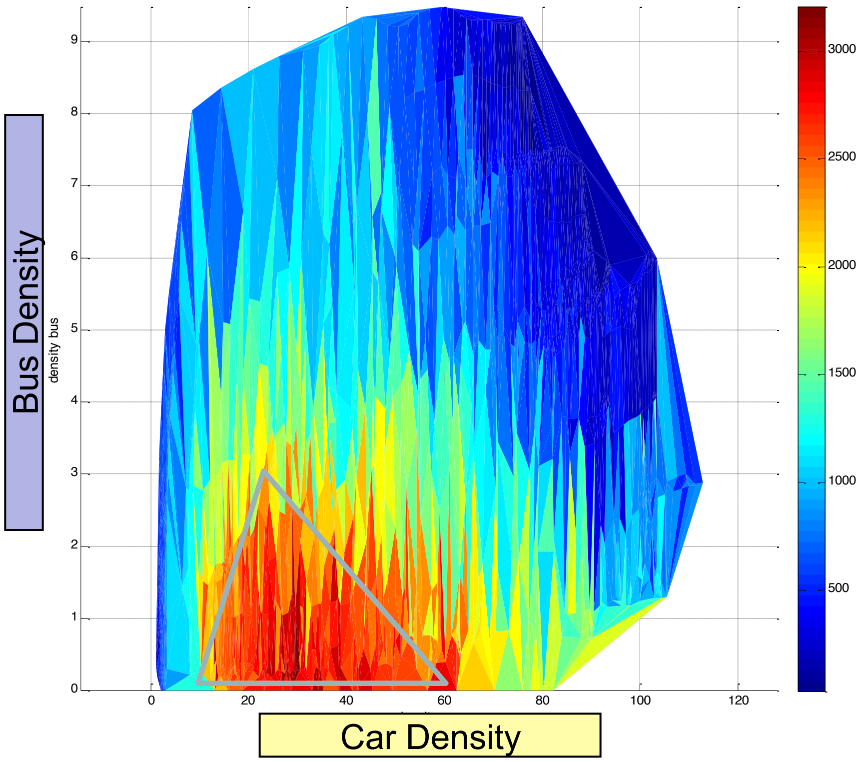
Costs (Users, Providers, etc.)

Road Space Used

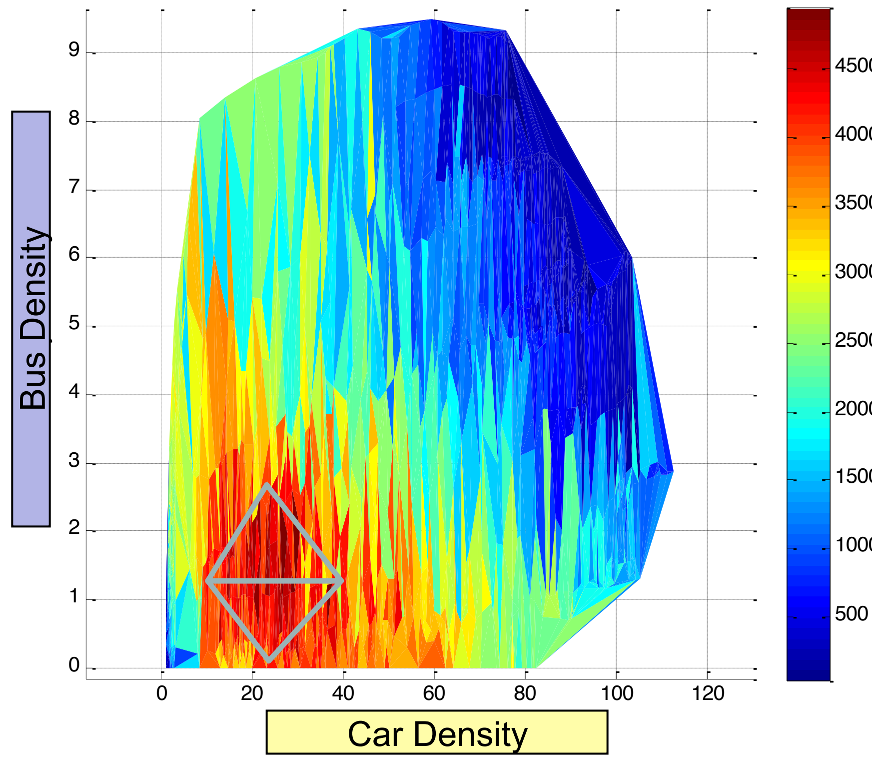
Multimodal Passenger oriented SoS Vision



Network performance measures



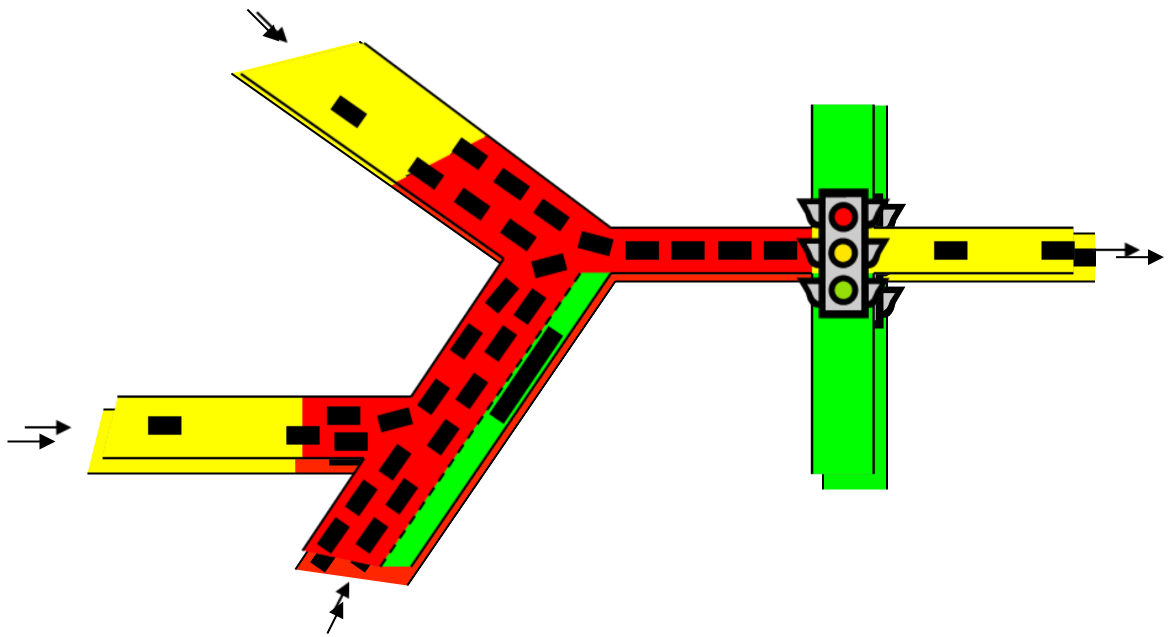
VEHICULAR FLOW



PASSENGER FLOW

Simulated data – Downtown SF

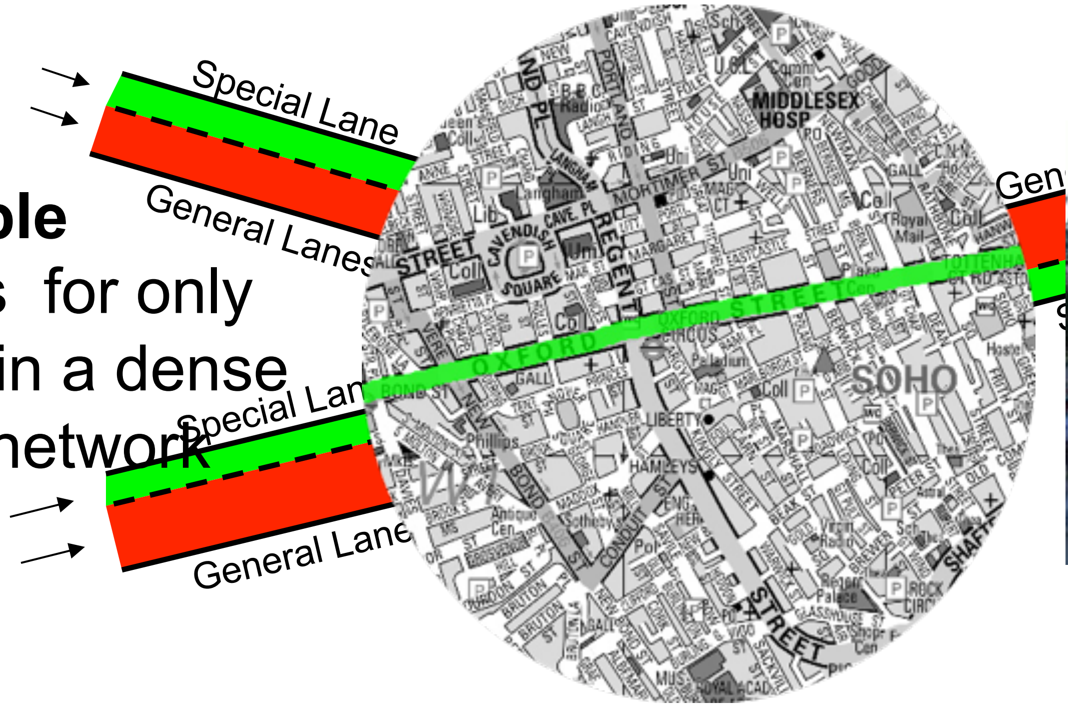
Infrastructure not equally available throughout a city



Queues form at locations with limited capacity, but spill-over to other locations

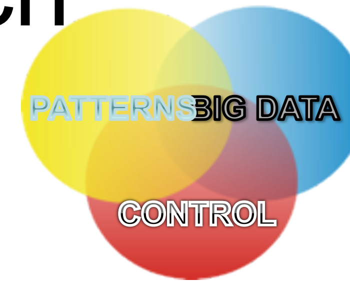
Need not provide special lanes everywhere

Example
Streets for only buses in a dense urban network



Provide bypasses for more efficient modes around much (if not all) congestion

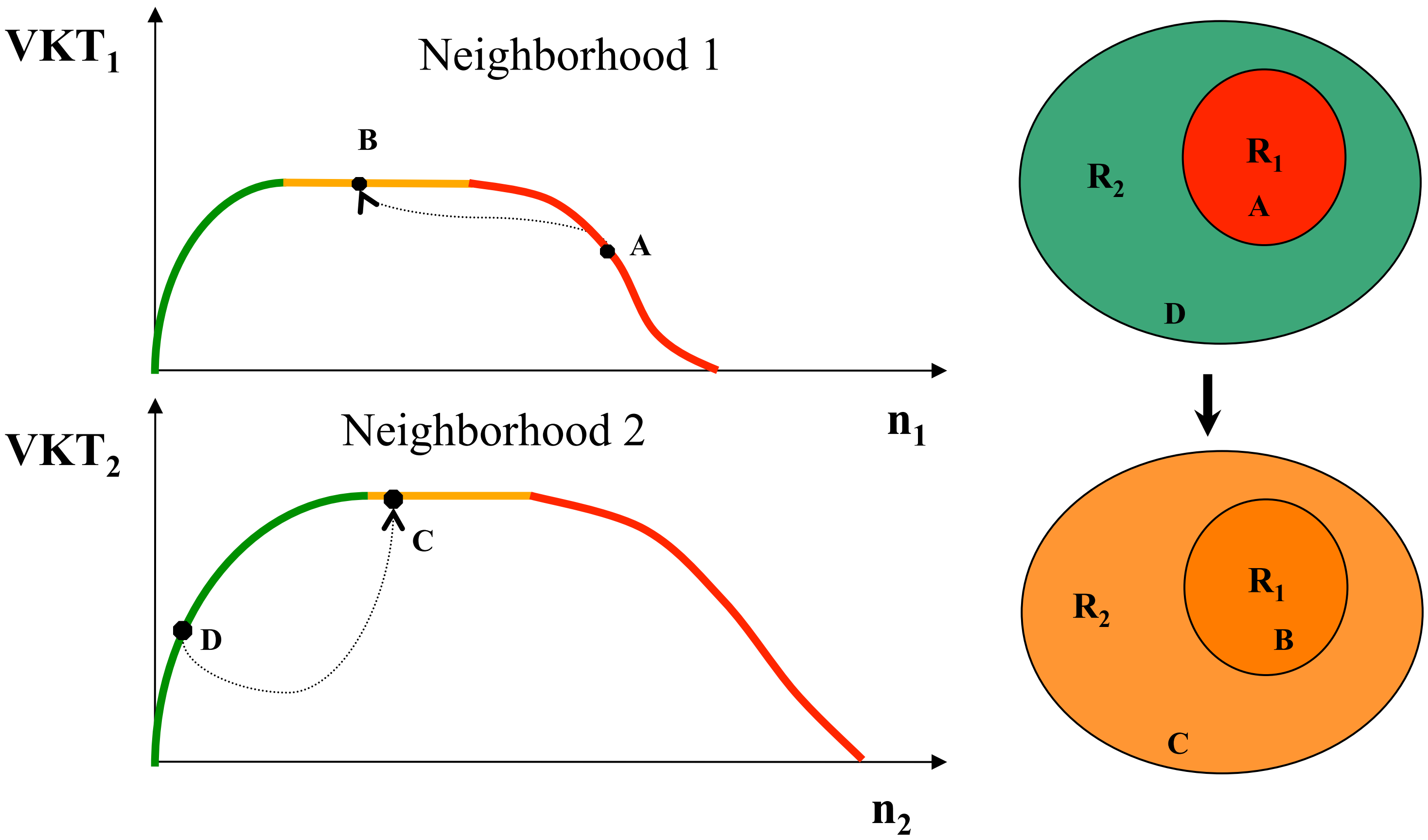
A “System of Systems” Approach



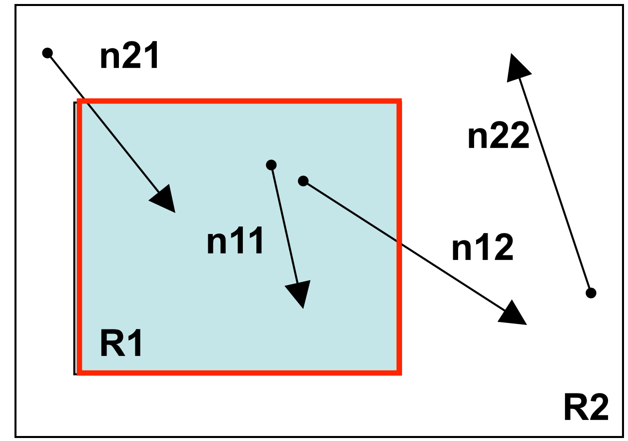
CONTROL

- **Without affecting # trips per mode**
  - **Hierarchical Signal Control**
- **By affecting # trips per mode**
  - **Urban Space Allocation**
  - **Bus Priority**
  - **Parking**

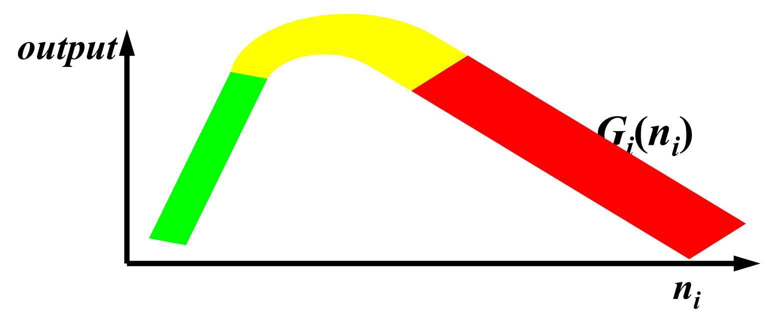
Macroscopic Perimeter control



Dynamics of a 2-reservoir system

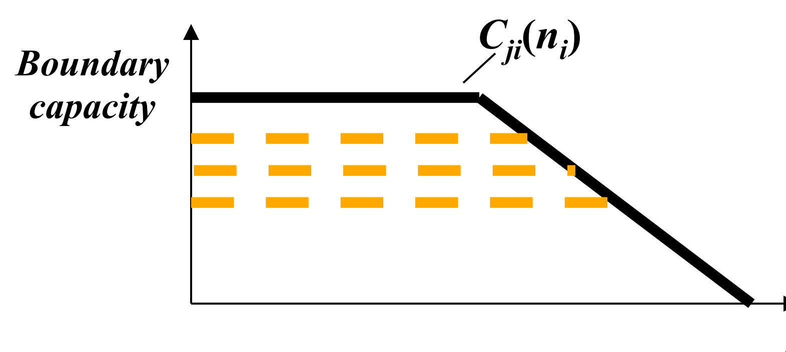


- State Variables
- Boundary Capacity
- Dynamic Equations
- Control



$$\frac{dn_{12}}{dt} = q_{12} - \min\left(\square \cdot C_{12}(n_2), \frac{n_{12}}{n_1} \cdot G_1(n_1) \right)$$

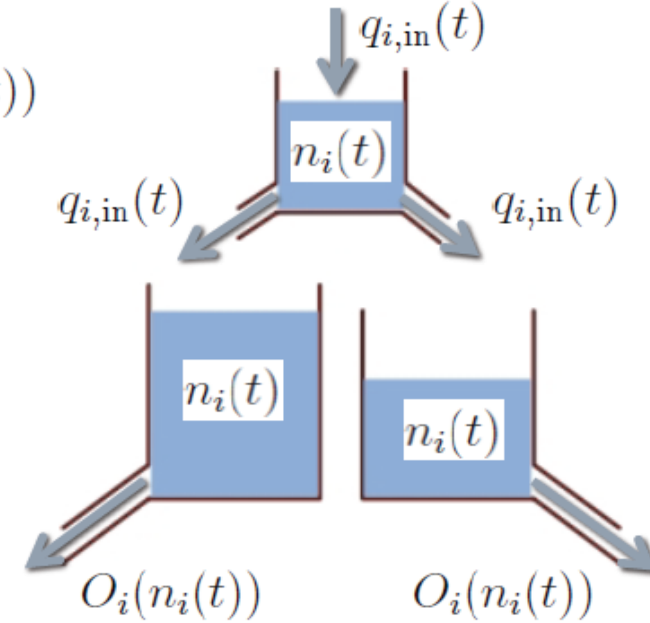
= IN - OUT



Multivariable Feedback Regulators

- **Given:** MFDs for each reservoir $O_i(n_i(t))$
- **Observe:** Accumulation $n_i(t)$
- **Control:** Input $q_{i,\text{in}}(t)$
- **Maximize:** Throughput
- **Minimize:** Risk overflow
- **Nonlinear Dynamics**

$$\frac{dn_i(t)}{dt} = q_{i,\text{in}}(t) - q_{i,\text{out}}(t) + d_i(t)$$



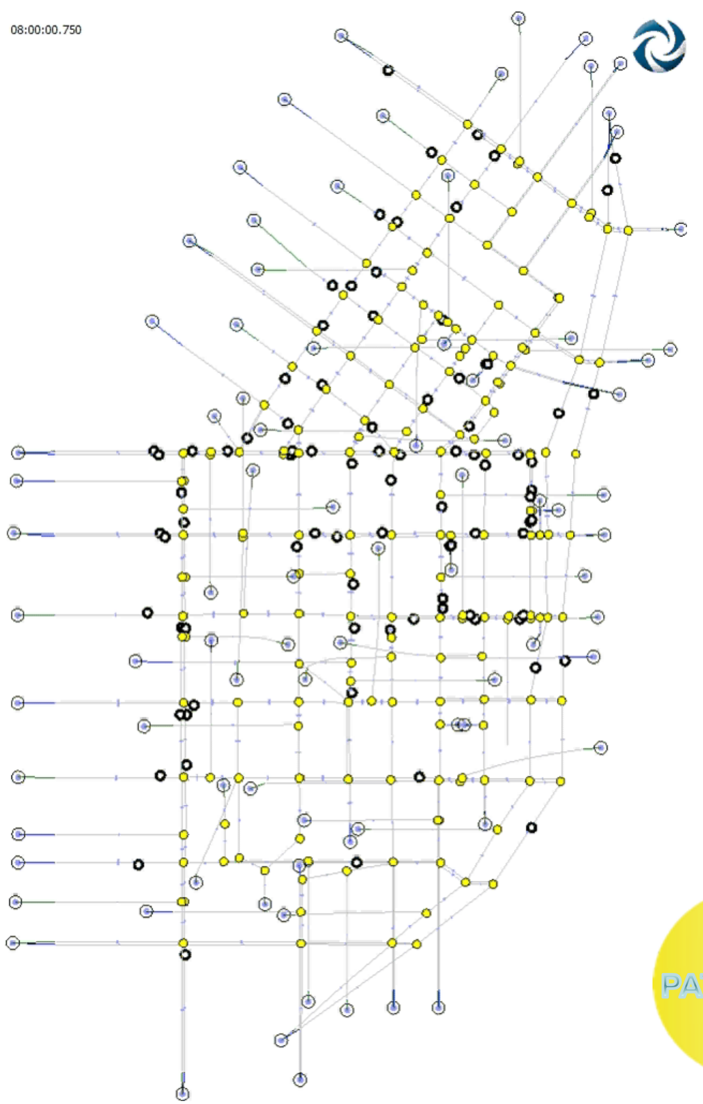
- **Linear-quadratic-integral control** (multivariable PI-regulators)

$$\beta(k) = \beta(k-1) - \mathbf{K}_p\left[\mathbf{n}(k) - \mathbf{n}(k-1)\right] - \mathbf{K}_I\left[\mathbf{n}(k) - \hat{\mathbf{n}}\right]$$

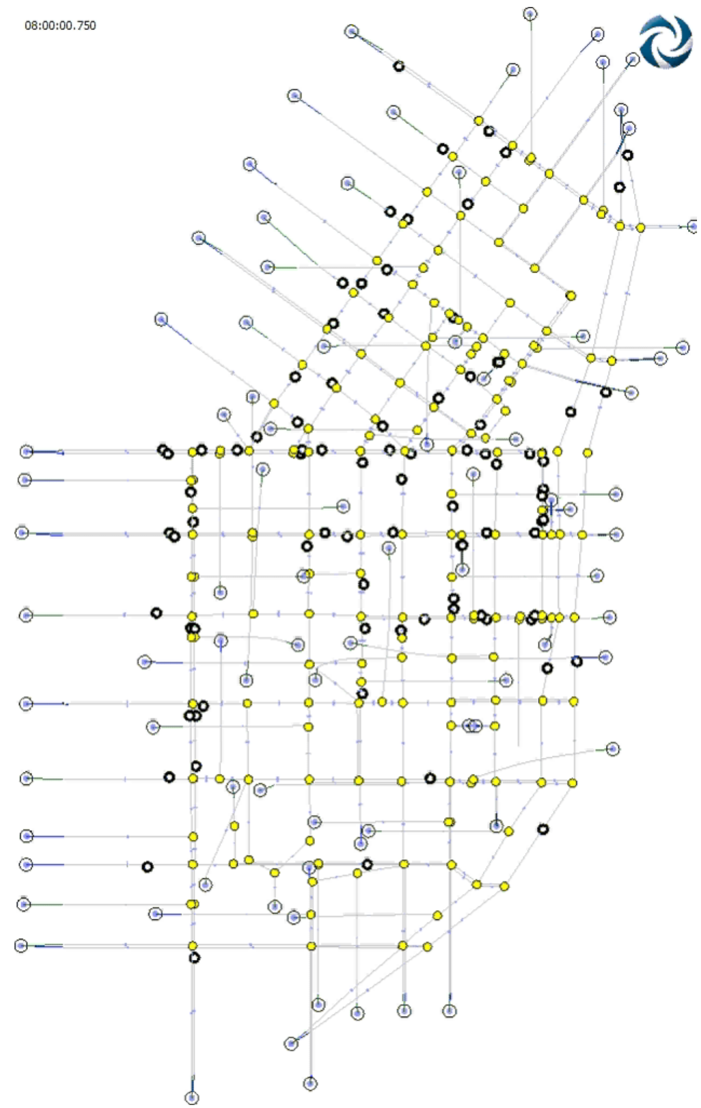
Aboudolas and Geroliminis (2013) – TR part B

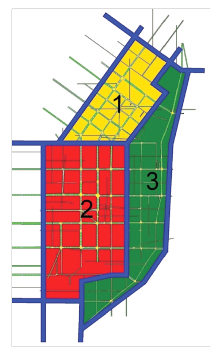
Simulation of multivariable PI

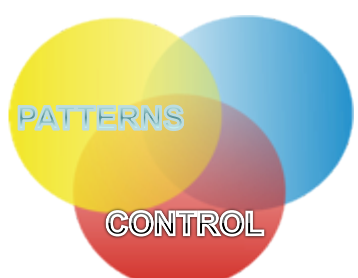
Pre-timed Traffic Control



Smart Traffic Control

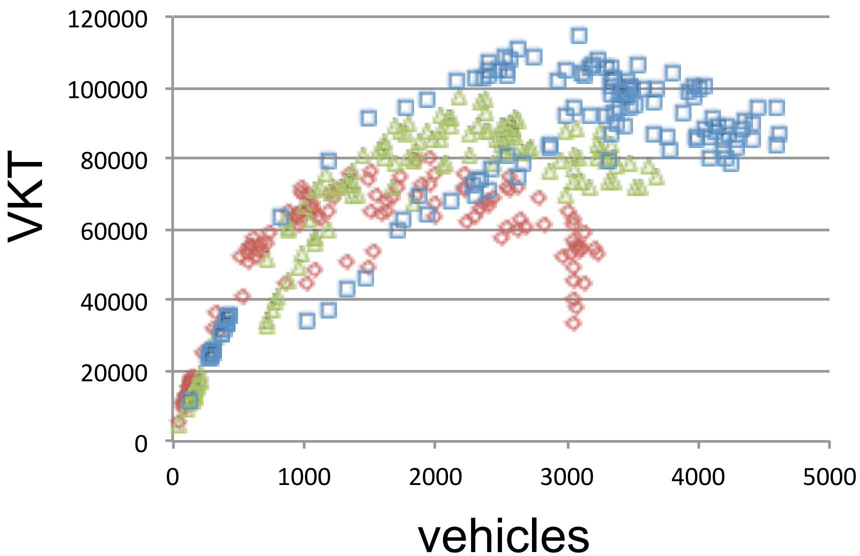


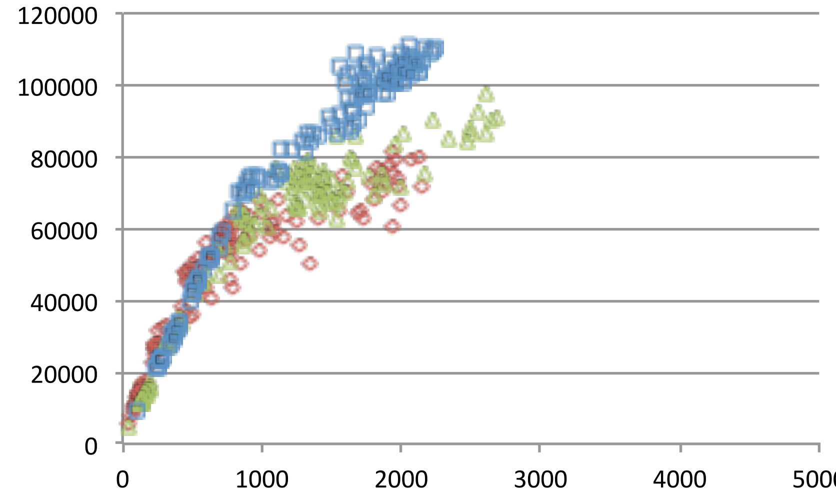




Aboudolas and Geroliminis (2013) – TR part B

Comparison with Other Controllers





Multiple MFDs perimeter + boundary controllers (NEW)

Pre-timed fixed control (PT)

Improvements (total vehicle delays)

- PT vs. NEW 30-35%

- Equitable distribution of queues
- Earlier activation of Control

Hierarchical SoS Control

High level MPC controller

$$J = \min_{U_{IJ},U_{JI}} \sum_{I\in\mathcal{R},J\in\mathcal{H}_I} \int_0^{t_f} \left(N_{II}(t) + N_{IJ}(t)\right)\mathrm{d}t$$

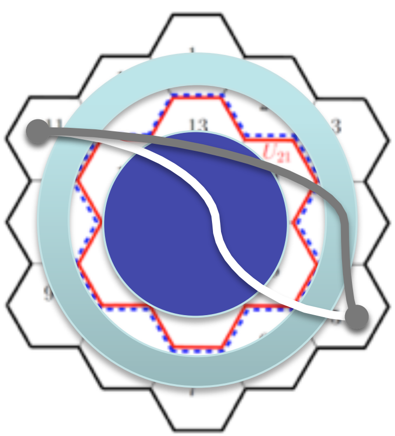
Low level I controller

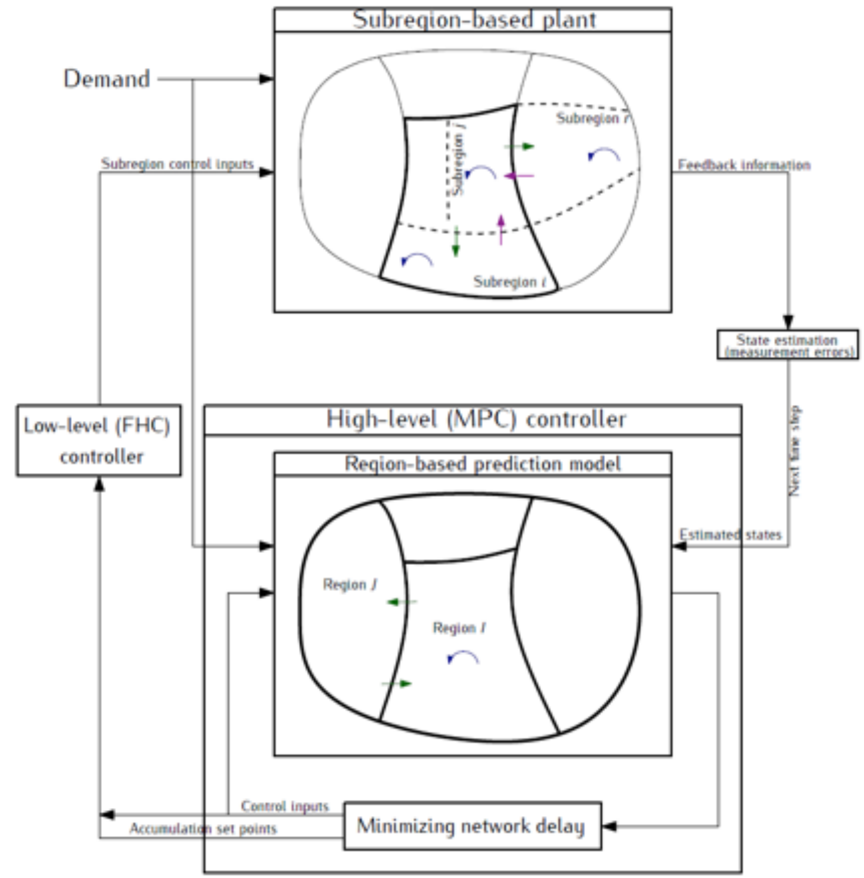
$$u_{ij}(k_c) = u_{ij}(k_c-1) + K_1 \cdot \left(\frac{N_J(k_c+K_p-1)}{|\mathcal{SR}_J|} - n_j(k_c)\right) - K_2 \cdot \left(\frac{N_I(k_c+K_p-1)}{|\mathcal{SR}_I|} - n_i(k_c)\right)$$

subject to:

$$\left|\sum u_{ij} - U_{IJ}\right| < \delta$$

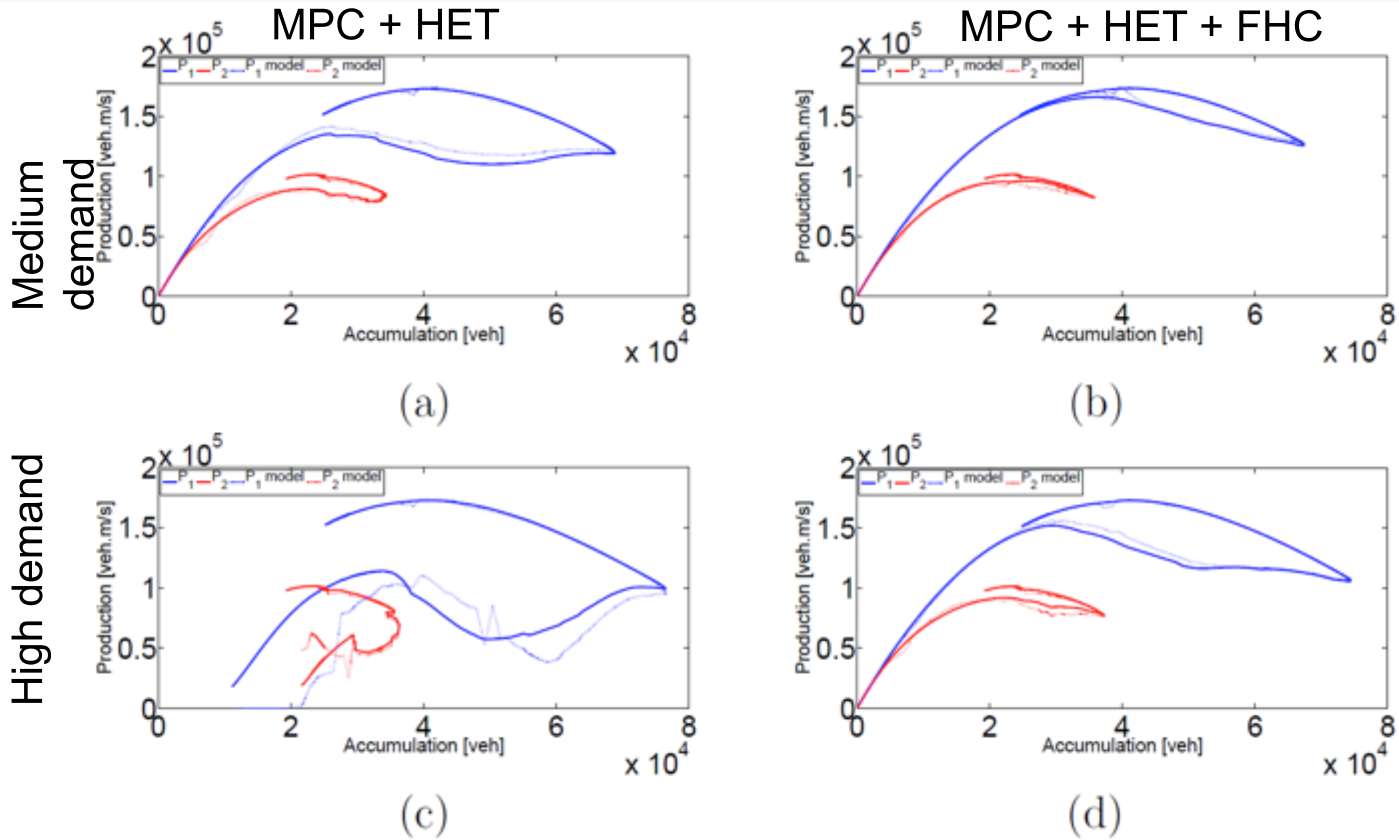
$$0 \le U_{\min} \le u_{ij}(k) \le U_{\max} \le 1$$





Haddad, Ramezani, Geroliminis (2012, 2013, 2014) – Trans. Res. Part B and IEEE Transactions on ITS

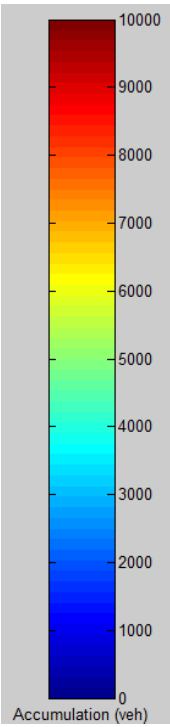
Results



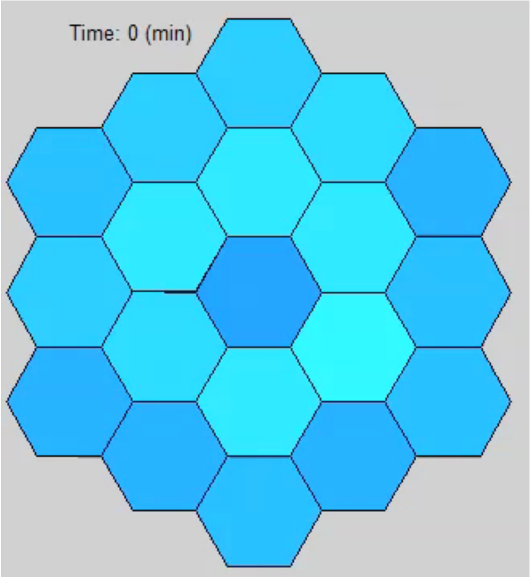
Total network delay (veh.sec × 10^6)

Demand	No Control	MPC	MPC+ HET	MPC+FHC	MPC + HET + FHC
Medium	1069.4	573.8	546.2	541.9	518.0
High	1204.4	930.5	881.5	851.0	636.8

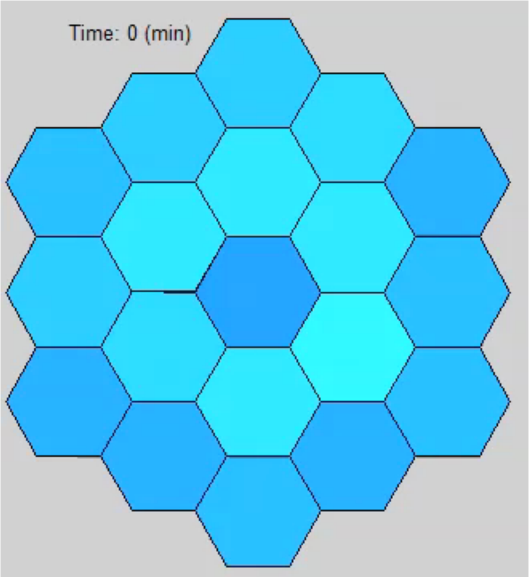
Results



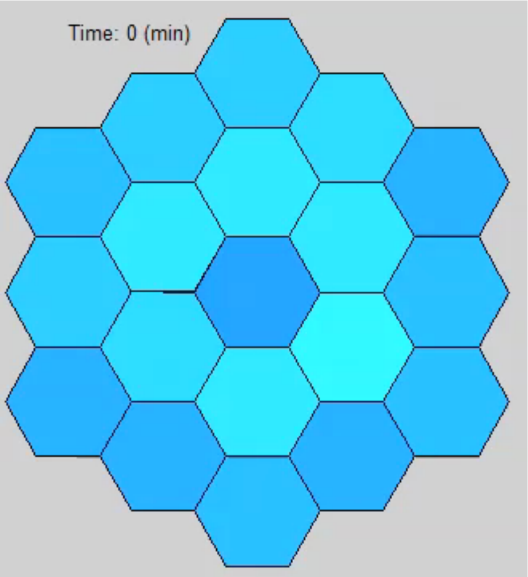
No Control

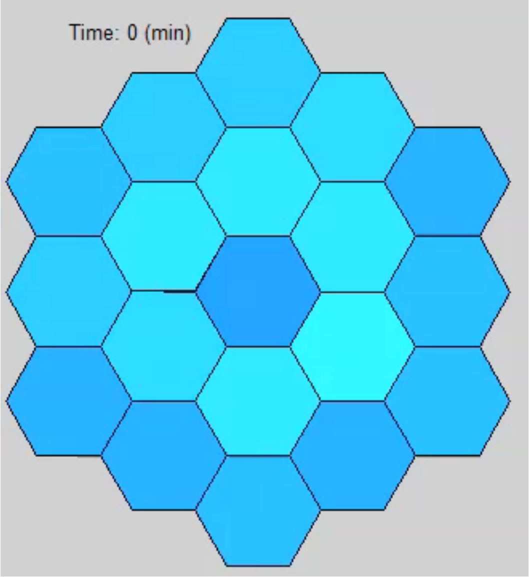


MPC

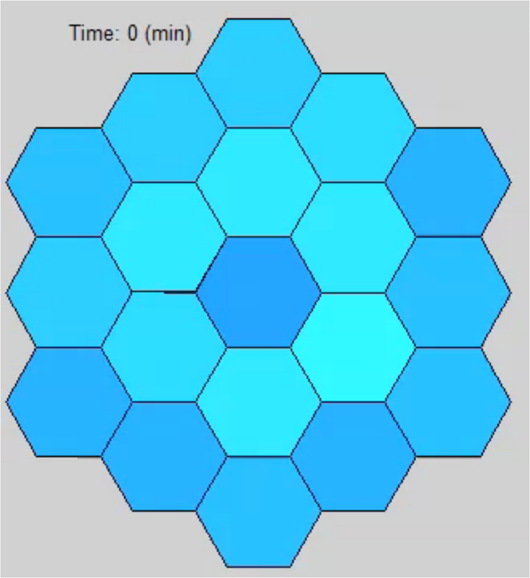


MPC+HET





MPC+FHC



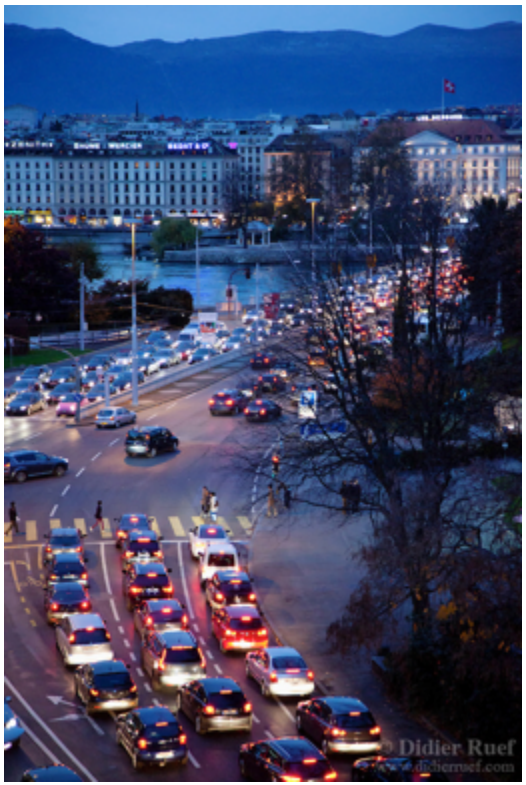
MPC+HET+FHC

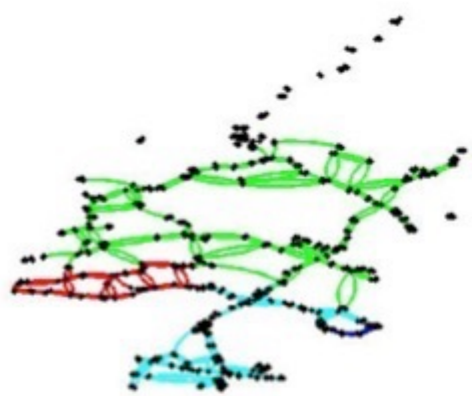
Under design field tests

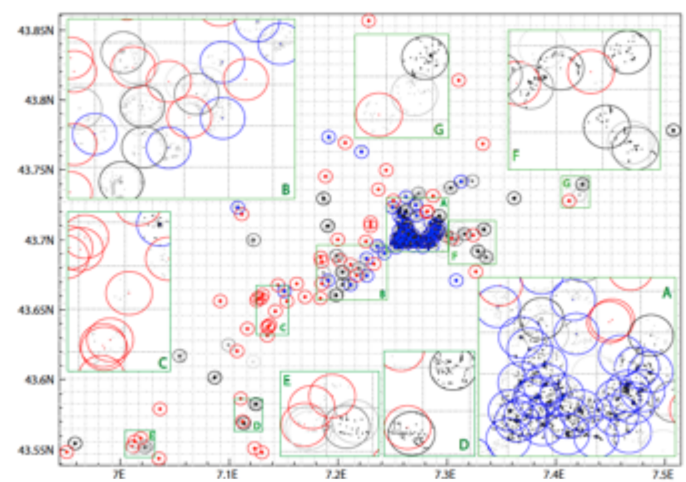
Geneva, CH

Sydney AUS

Nice, France







Passenger flow optimization

Smart traffic control

One-way Car Sharing

Further research questions

- Control of more complex city structures
- Congestion Spreading in networks
- Travel time reliability and Control
- Multimodal city networks (People + Goods)
- Urban Logistics
- Car-sharing

DISCUSSION