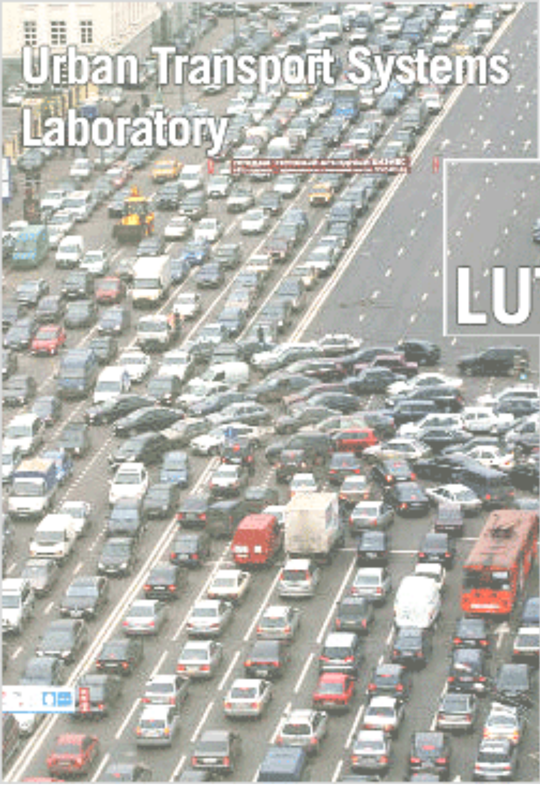


Modeling and Control of heterogeneous Traffic in cities

Prof. Nikolas Geroliminis

Urban Transport Systems Laboratory

INVENTEURS DU MONDE NUMÉRIQUE

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

ENAC School of Architecture, Civil and Environmental Engineering

Sophia Antipolis, March 21st, 2013

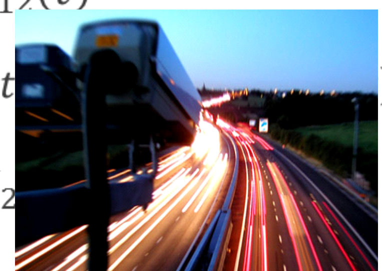
Complex Cities

$_1(t)$ $\int_{t_0}^{t_f}[n_1(t)+n_2(t)]dt + \sum_{k=0}^{K-1}\sum_{l=1}^{L} x_l(k)$

$_{,2}(k)$

Sub

- $\frac{d}{dt} = \frac{_{23}(t)}{\hat{q}_{321}(t)+q_{213}(t)+q_{21}(t)} u_{21} \quad + \hat{q}_{231}(t) + \hat{q}_{31}$
- $\frac{dn_{12}(t)}{dt} = q_{12}(t) + q_{123}(t) + \hat{q}_{312}(t) - u_{12}(t).M_{12}(t)$



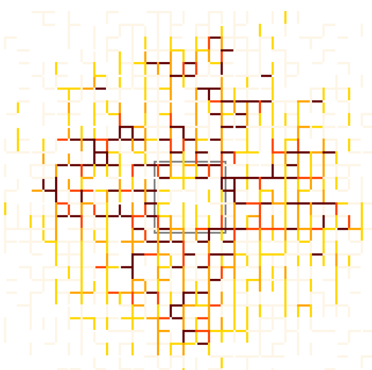
$\frac{q_{213}(t)}{q_{213}(t)+q_{21}(t)} u_{21}(t).M_{21}(t) + q_{13}(t \quad) - \min(M_{13}(t), C_{or,1}(t))$

$+ q_{213}(t) + \hat{q}_{321}(t) - u_{21}(t).M_2$

$(t)+ q \quad + q_{22}(t) + q_{132}(t) + q_{32}(t)$

$q_{12}(t)$

- $\frac{dn_{23}(t)}{dt} = \frac{q_{123}(t}{\hat{q}_{312}(t)+ q_{12}(t)} \quad + q_{23}(t) + q_{231}(t) - \min(M_2$



$ax - n_{or,i}(k))/T_k$

$_1(t) \le u_{max} \; ; u_{min} \le u_{or,1}(k), u_{or,2}(k) \le u_{max}$

$n \quad ; n_1(t) = \quad _{13}(t)$

$m \quad ; n_2(t) = \quad _{23}(t)$

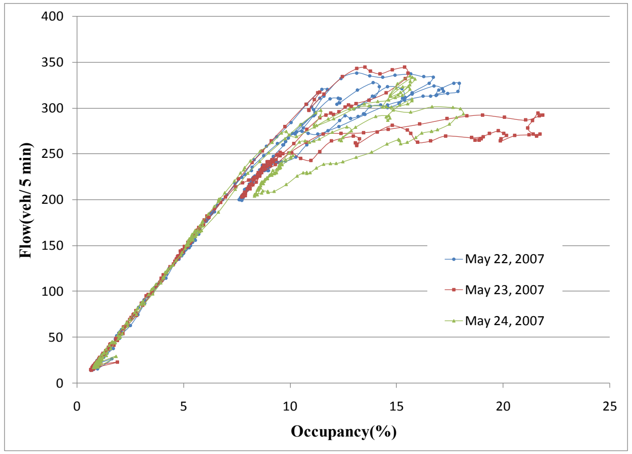
LUTS team


Nikolas Geroliminis
Jack Haddad (PostDoc) (CE – Control)
Konstantinos Aboudolas (Post Doc) (EE)
PhD Students
Burak Boyaci (OR)
Mohsen Ramezani (EE)
Yuxuan Ji (CS)
Nan Zheng (CE)
Mehmet Yildirimoglu (CE)
EPFL
LUTS - URBAN TRANSPORT SYSTEMS LABORATORY

Big challenges in complex transport systems

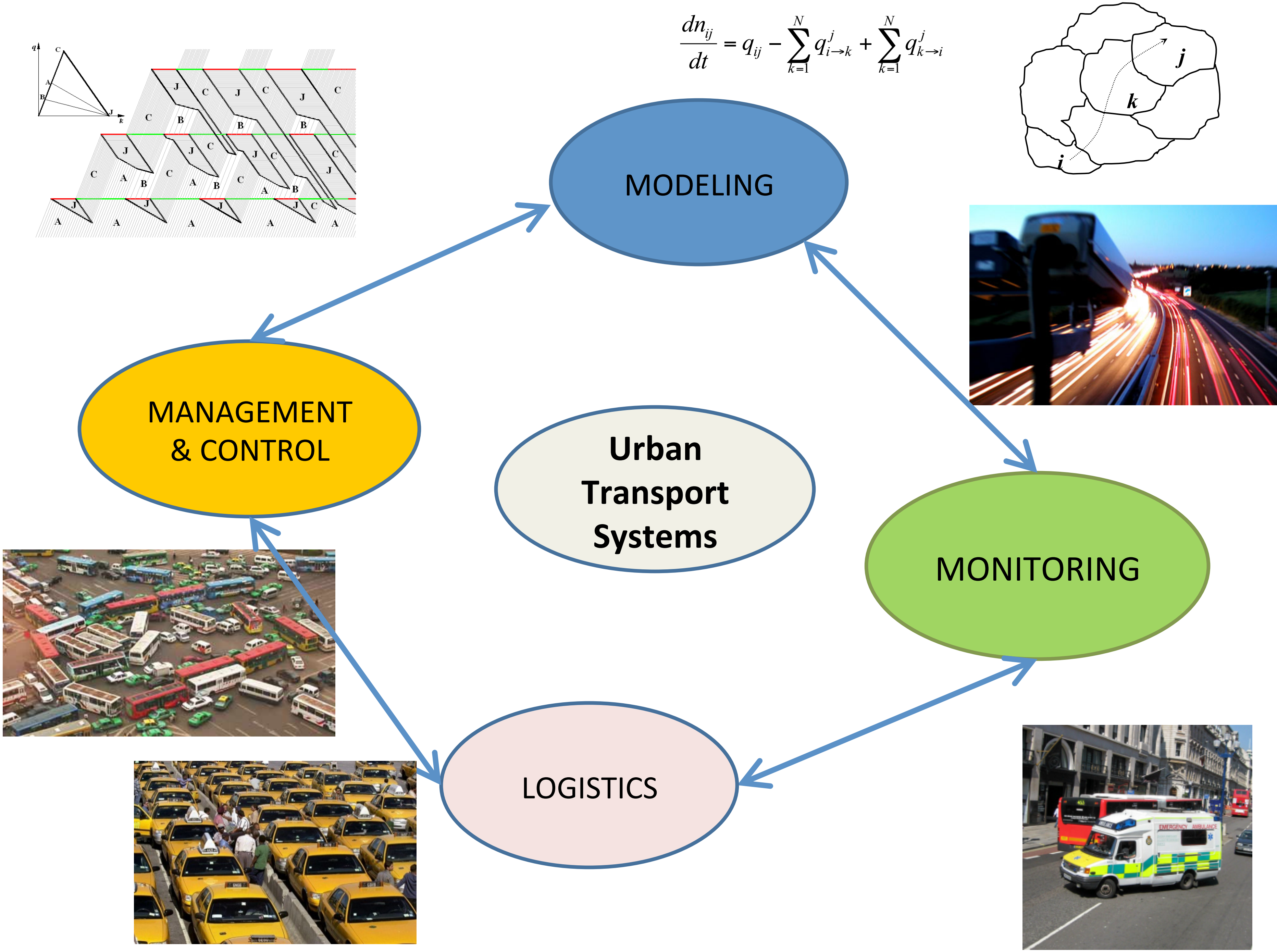
Non-linear interactions

- Components influence the system and vice versa
- Components adapt
- Causes and effects not proportional - Hysteresis
- Spreading phenomena
- Transient states



- Limits to predictability
- Complex Dynamics
- Chaotic Behavior
- Sensitivity

- Limits to Control
- Instabilities
- Irreducible randomness
- Local Optima
- Multi-objective Optimization
- State Estimation

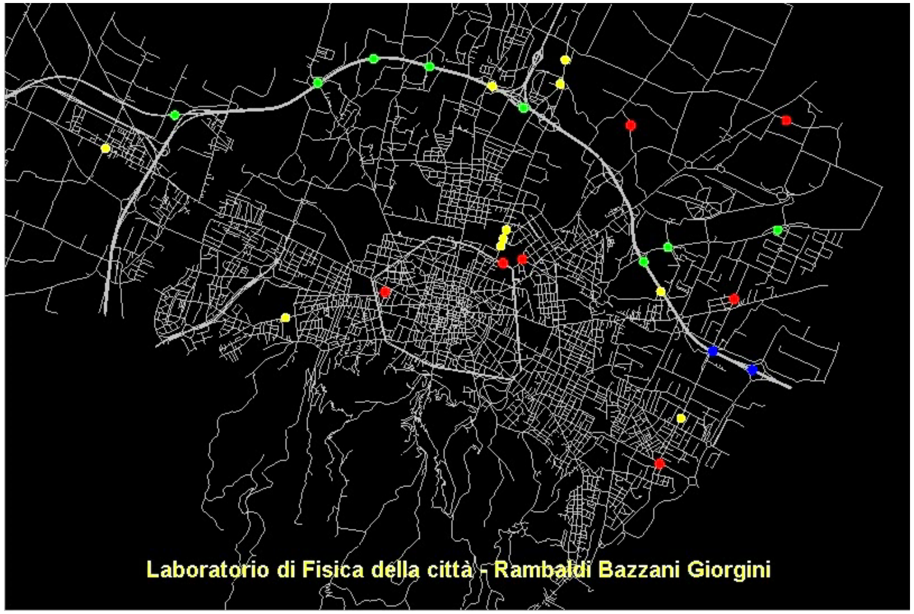


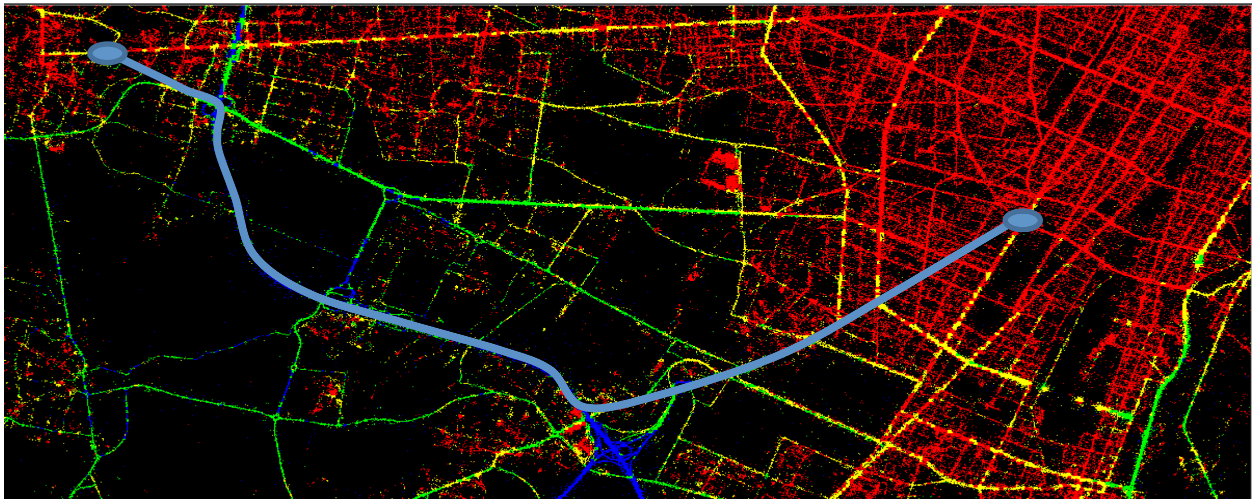
$\frac{dn_{ij}}{dt} = q_{ij} - \sum_{k=1}^{N} q_{i \to k}^{j} + \sum_{k=1}^{N} q_{k \to i}^{j}$
MODELING
MANAGEMENT & CONTROL
Urban Transport Systems
MONITORING
LOGISTICS

MONITORING

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

Sparse multi-sensor data





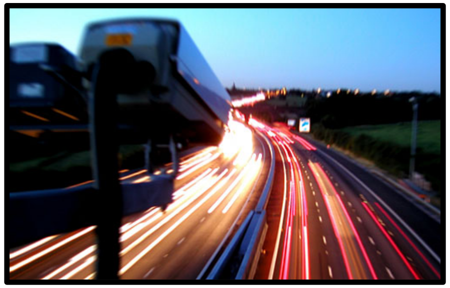
Pictures provided by Prof. Bazzani

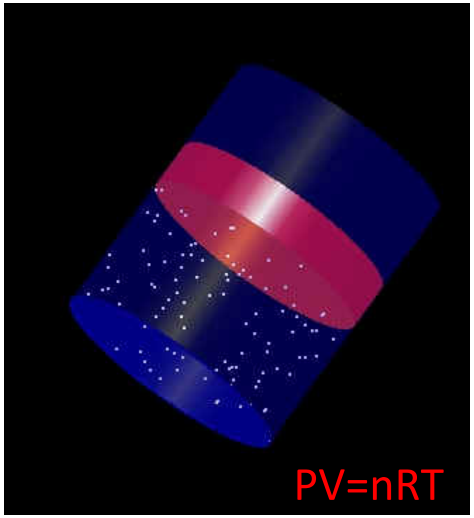
WHY AGGREGATED?

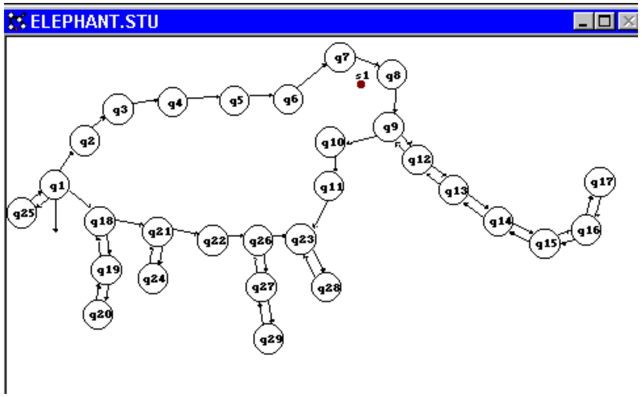
- Humans make choices in terms of routes, destinations and driving behavior (unpredictability – related to control)

- Not a clear distinction between free-flow and congested traffic states (complexity of traffic states)

- Need for real-time hierarchical traffic management schemes





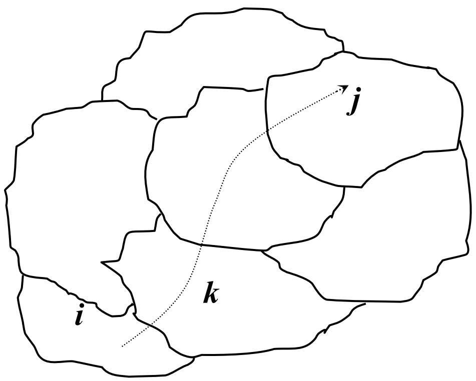


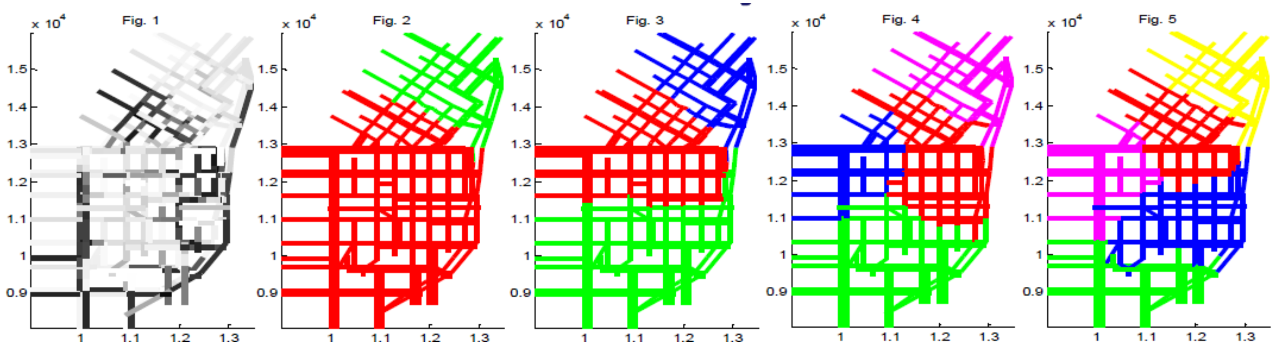
"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk".
JOHN VON NEUMANN

Solution (?):
A network based aggregated approach

Challenges of spatial aggregation

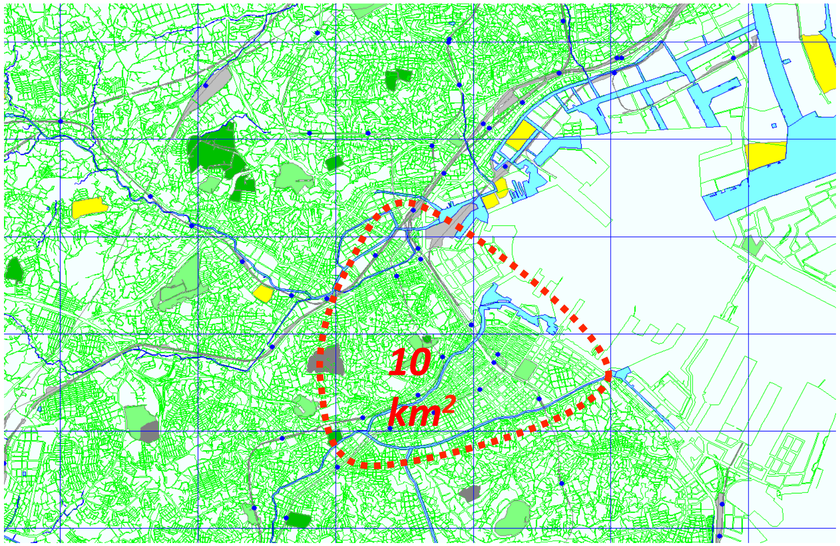
- Physical Properties of aggregated models
- Macroscopic Fundamental Diagram (MFD)
- Partitioning (static, dynamic)
- Hierarchical control
- Multimodality

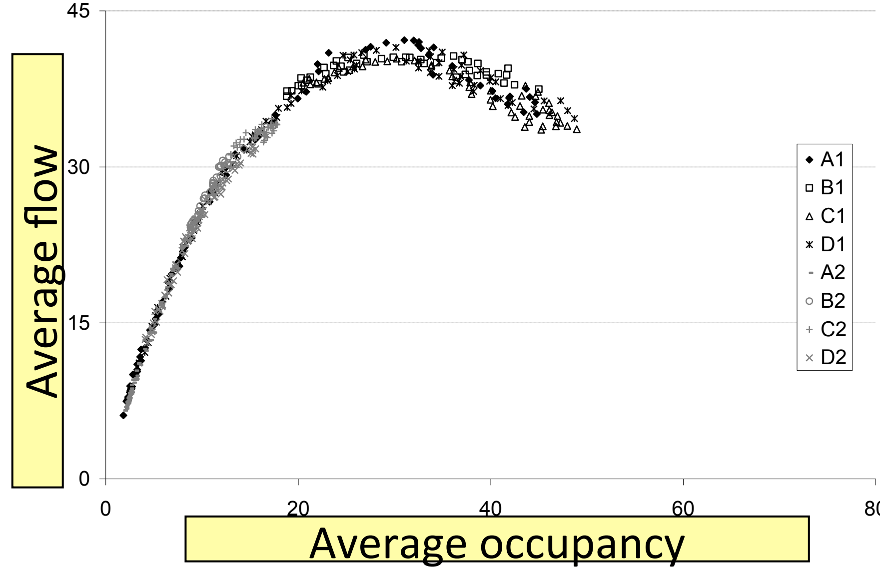


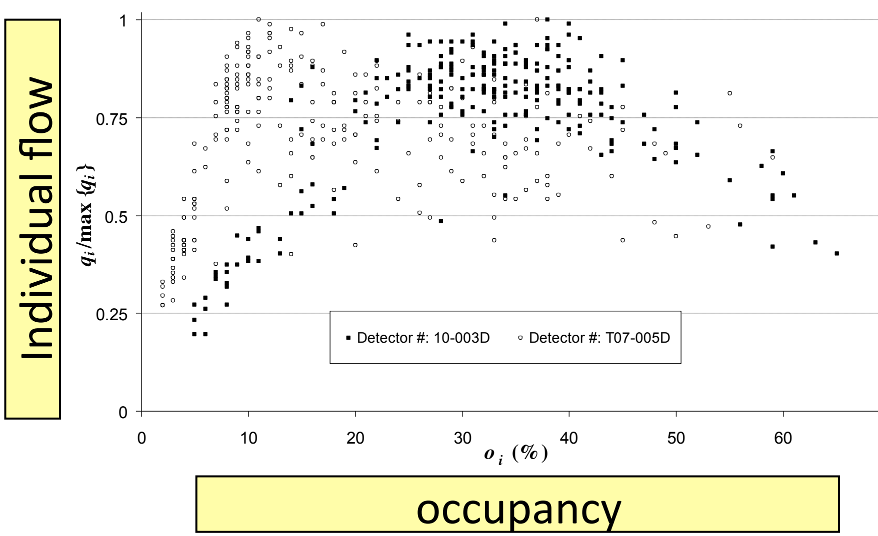


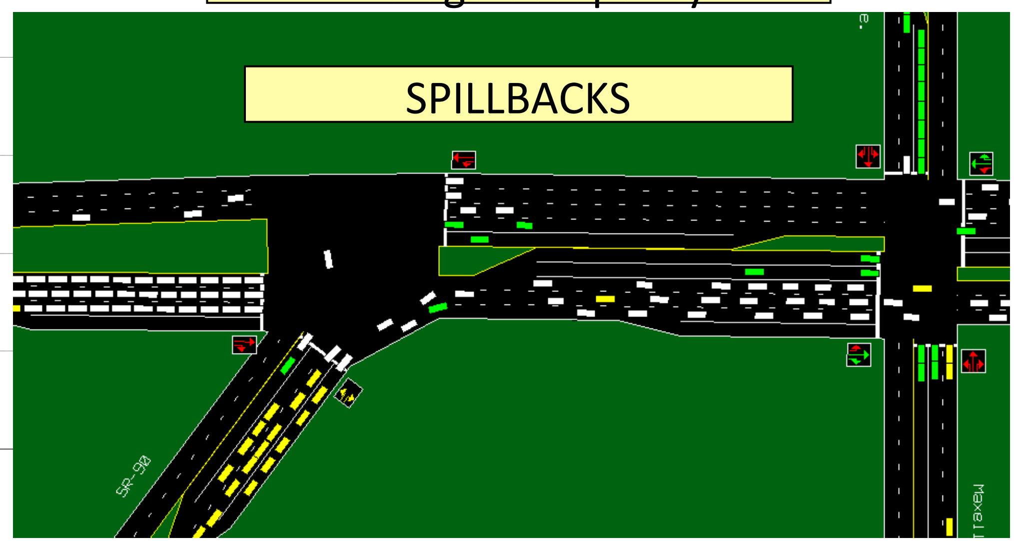
AGGREGATE BEHAVIOR
= ?
SCALED UP VERSION OF LINK BEHAVIOR

MFD Empirical results





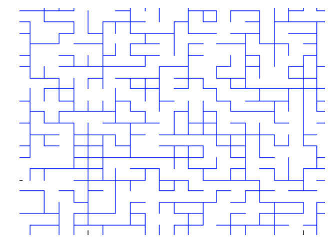


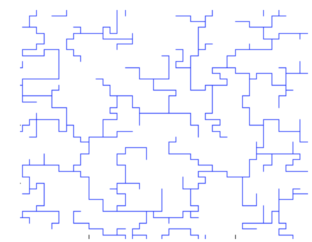


Geroliminis and Daganzo (2008) – Tr. Res. Part B

Network type and MFD

MFD **IS NOT** A UNIVERSAL LAW



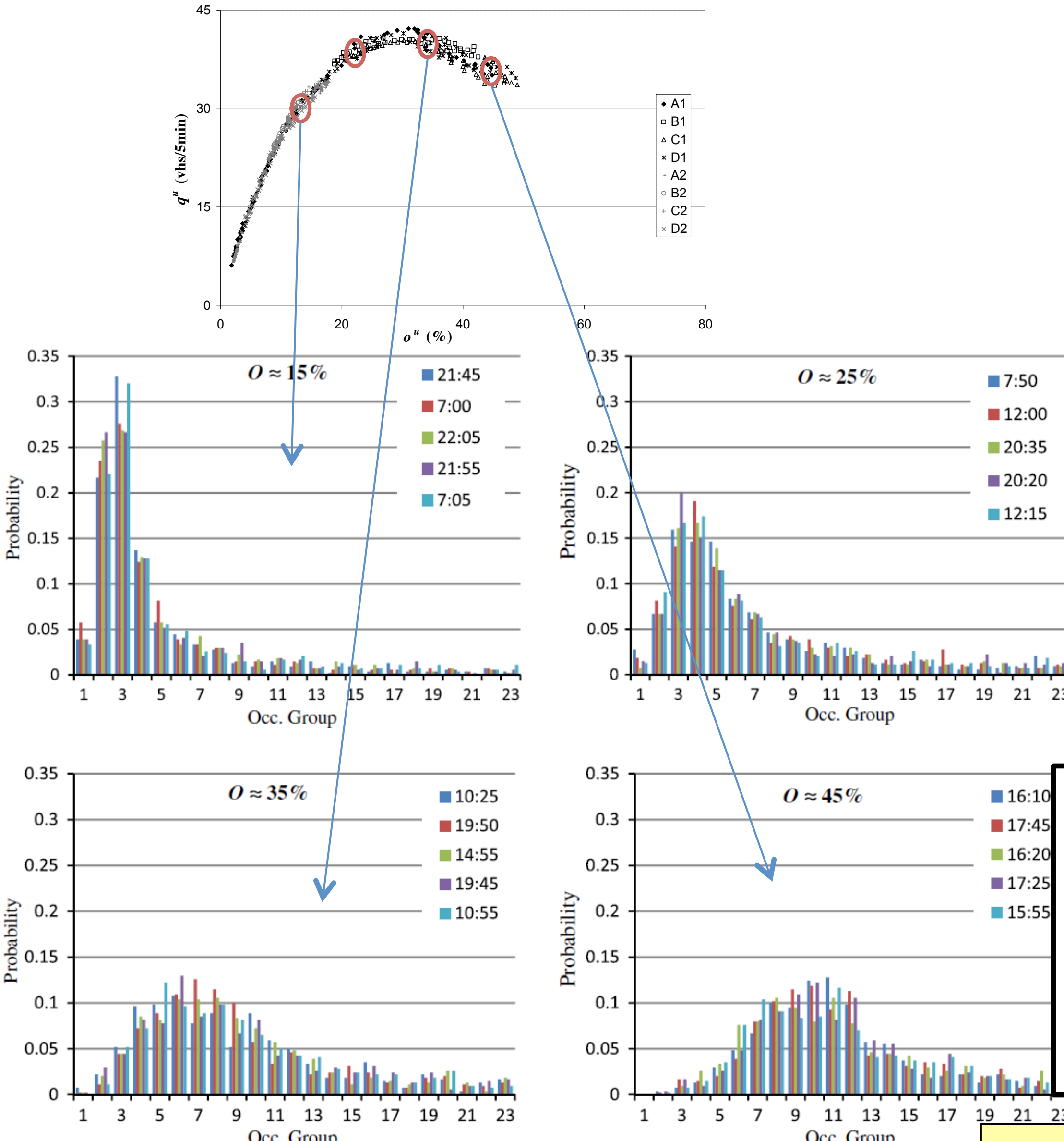


Regularity conditions that possibly ensure an MFD

- 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

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

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

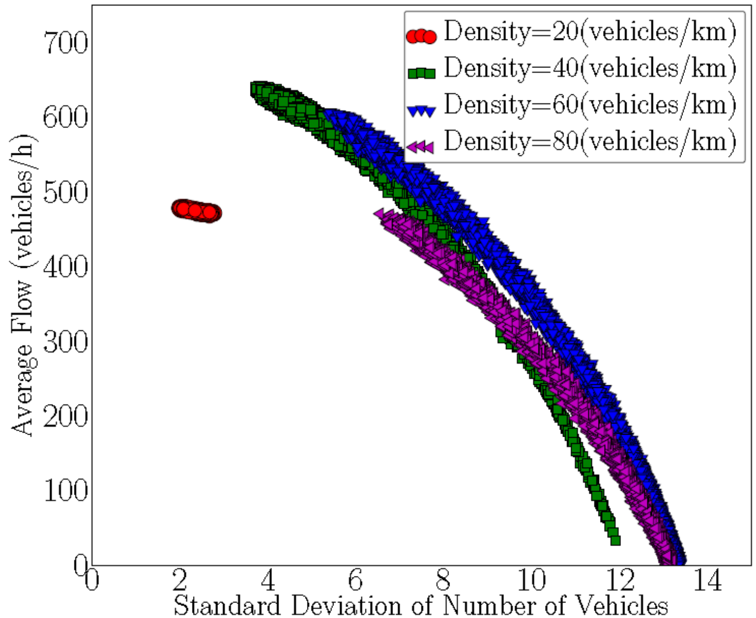
Variance much higher than binomial's

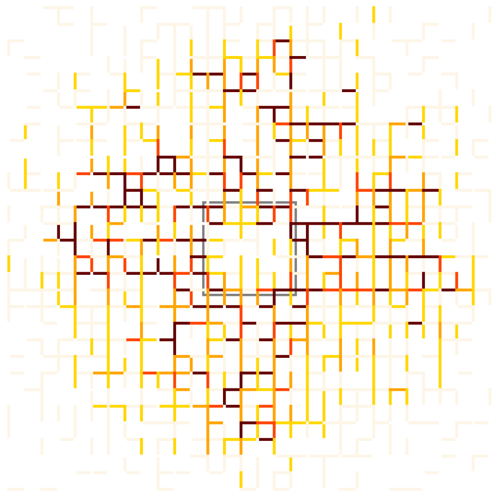
WHY?

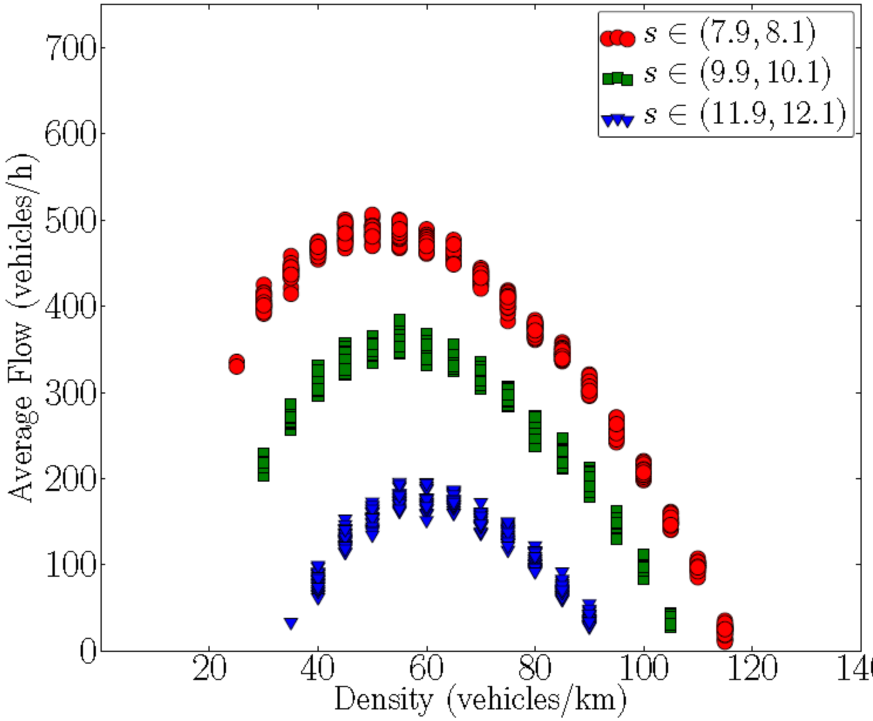
Correlation of link density (propagation)

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

Spatial Variability and Network Capacity





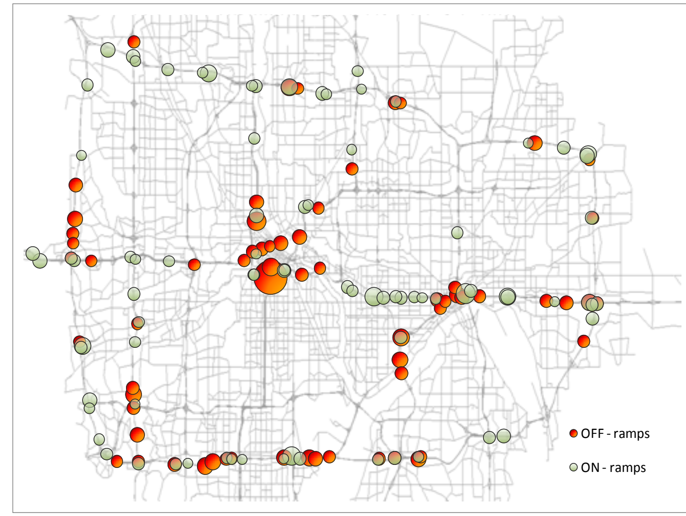


Mazloumian, Geroliminis and Helbing (2010) – Ph.Trans.Roy. Soc. A

Freeway MFDs (A “bad” example)

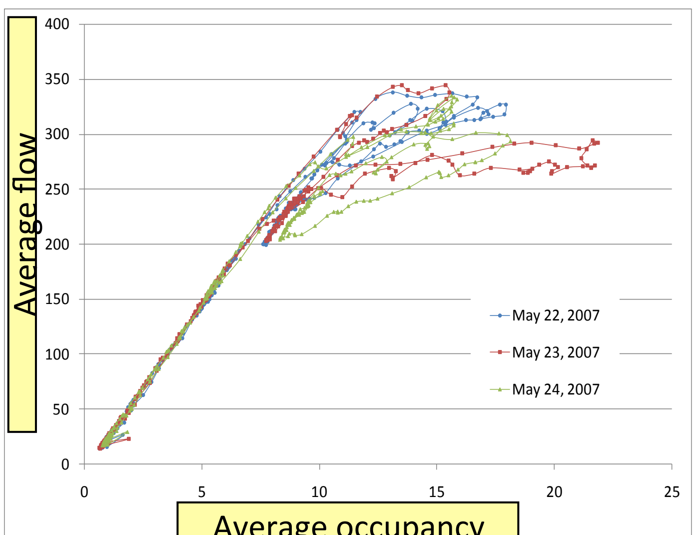
- **Strong hysteresis phenomena in freeway MFDs**

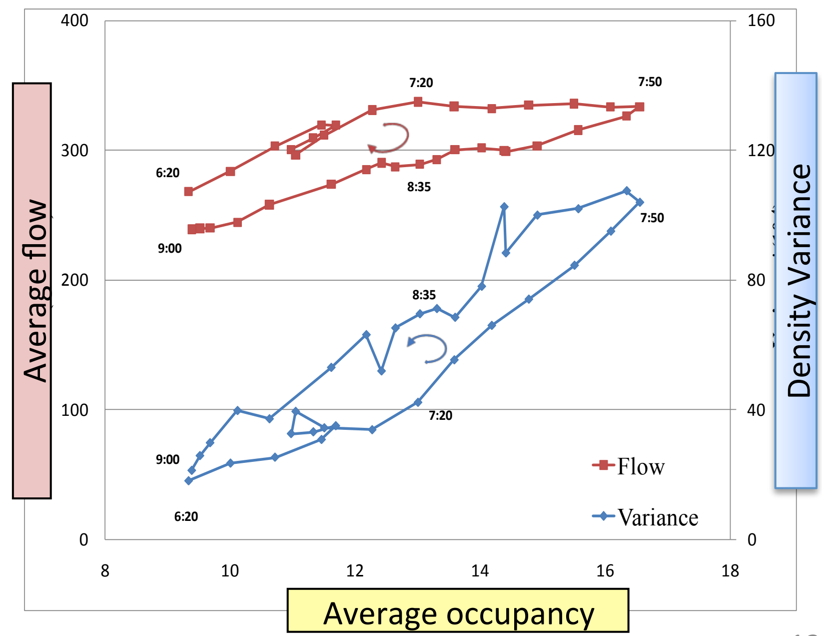
Freeway network of Minneapolis (USA)



EXPLANATION

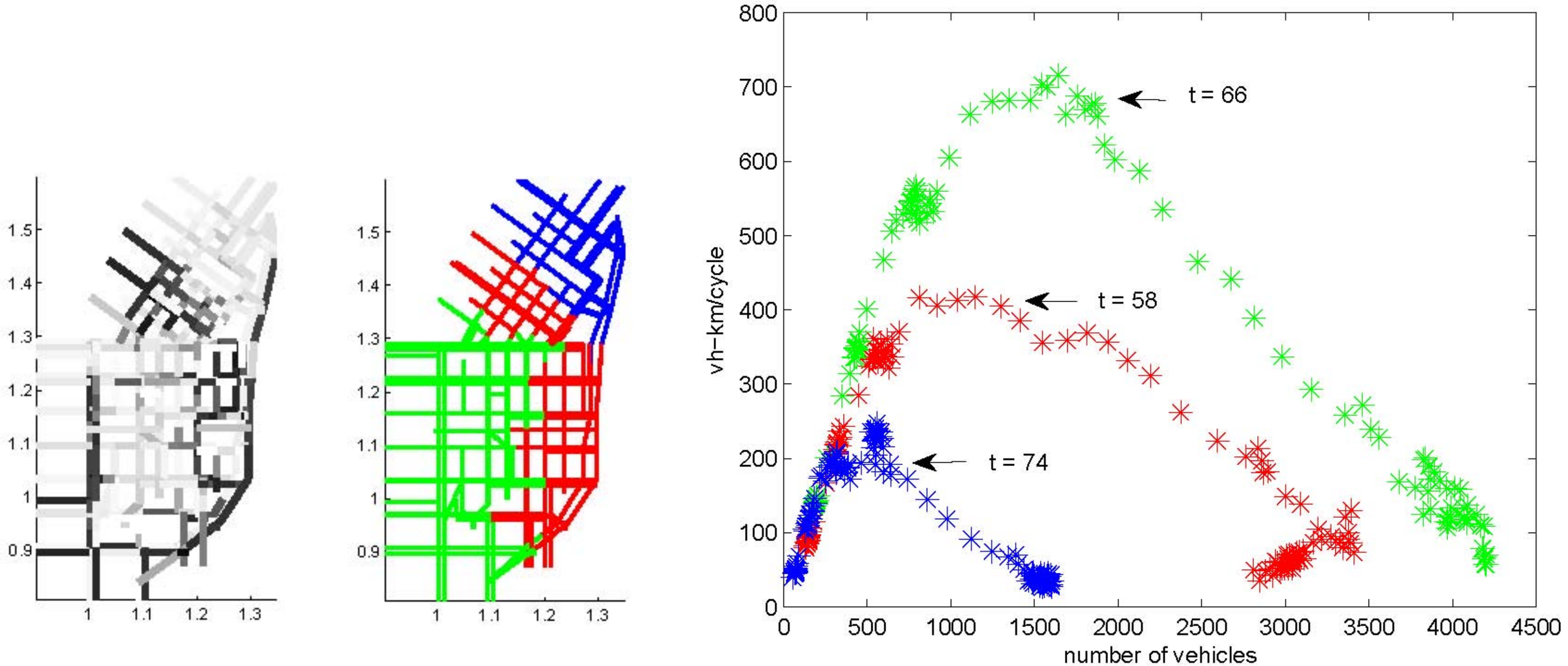
- Different distribution of congestion (onset vs. offset)





Geroliminis and Sun (2011) – ISTTT 19

Congestion Spreading – Intro to Partitioning



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

Network static partitioning

Objectives

- Smooth boundaries (for control)
- Spatial Compactness
- Small heterogeneity within regions

1. Initialization (Ncut)
2. Merging
3. Boundary Adjustment (Fine tuning)

Min $$NS_k = \frac{\sum_{A \in C} NS_k(A)}{k}$$

where

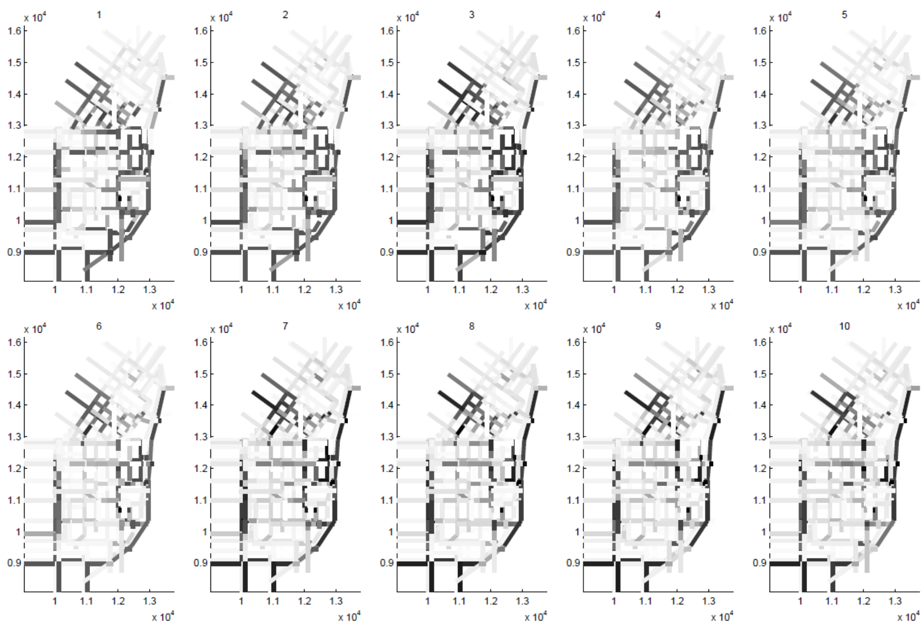
$$NS_k(A) = \frac{NS_k(A,A)}{NS_k(A,B)}$$

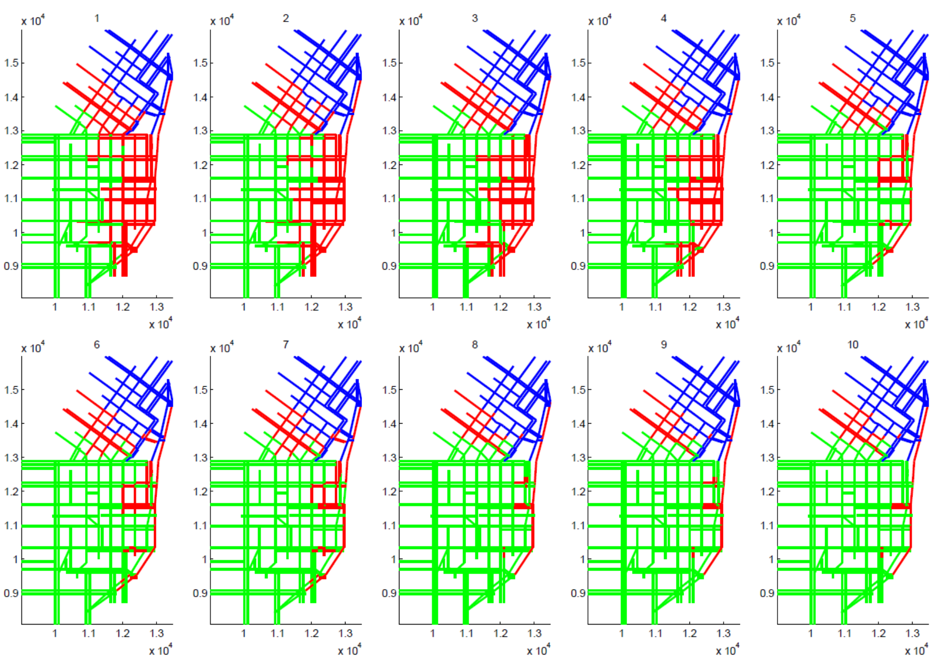
Intra-Similarity

Inter-Disiimilarity

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

Congestion spreading identification





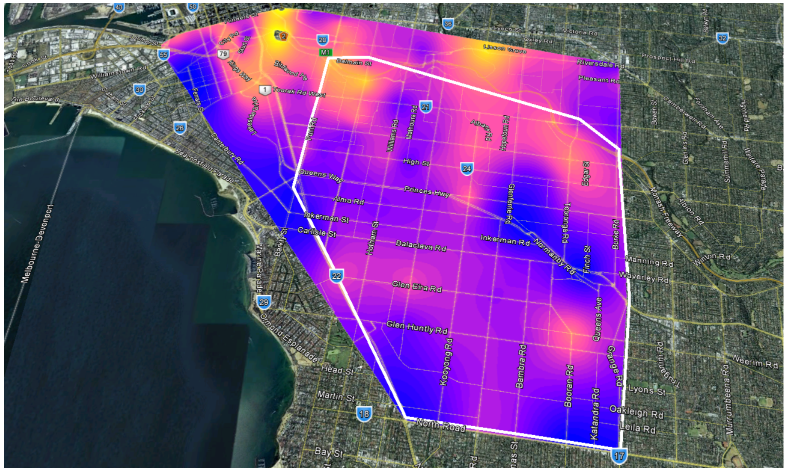
SIMPLE LOGIC

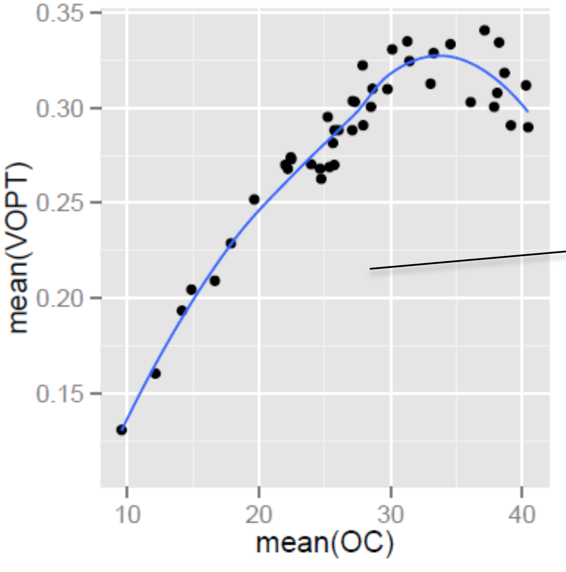
- Apply full algorithm at time t=0
- Apply only fine tuning for t>0

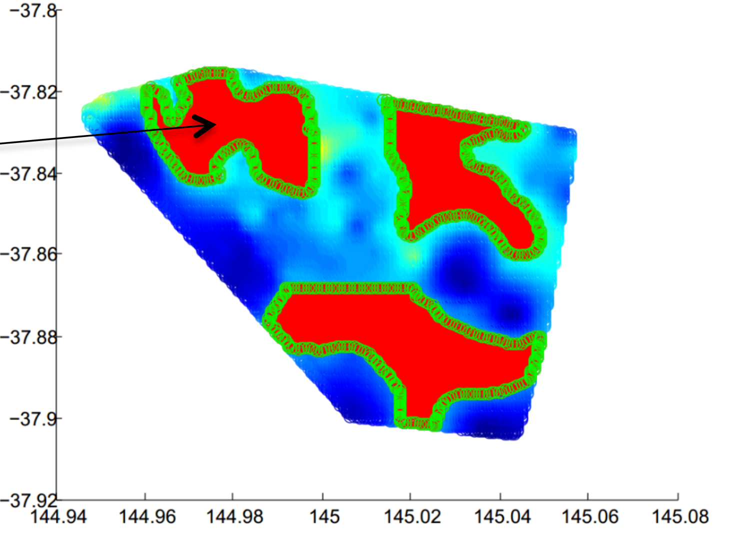
- New pockets of congestion are missing

Australian case study

- Melbourne Sydney
- Perimeter Control Case Study is prepared for beginning of 2014
- More than 5000 loop detector data



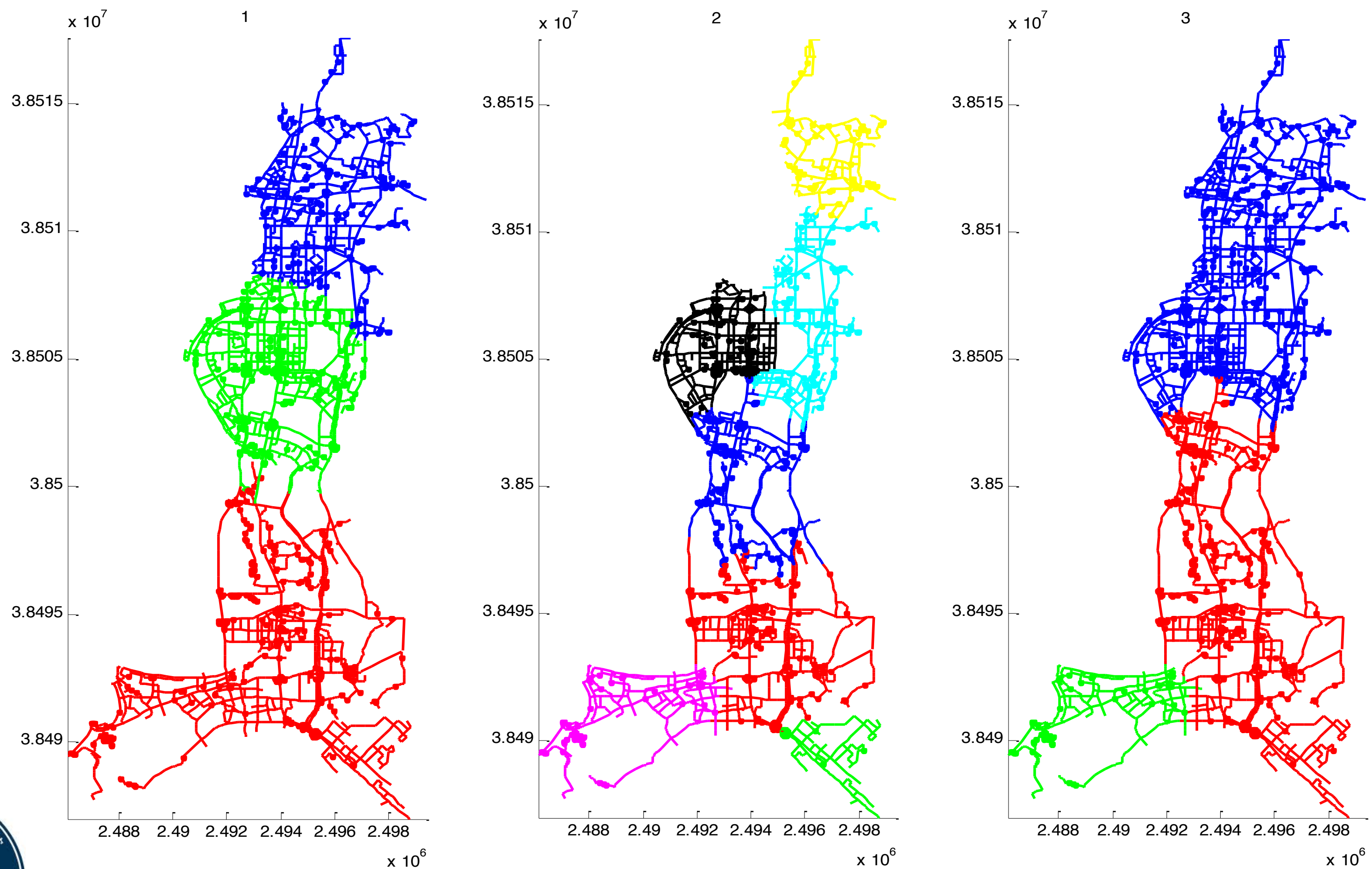




Ongoing

Dynamic Partitioning
Shenzhen case study

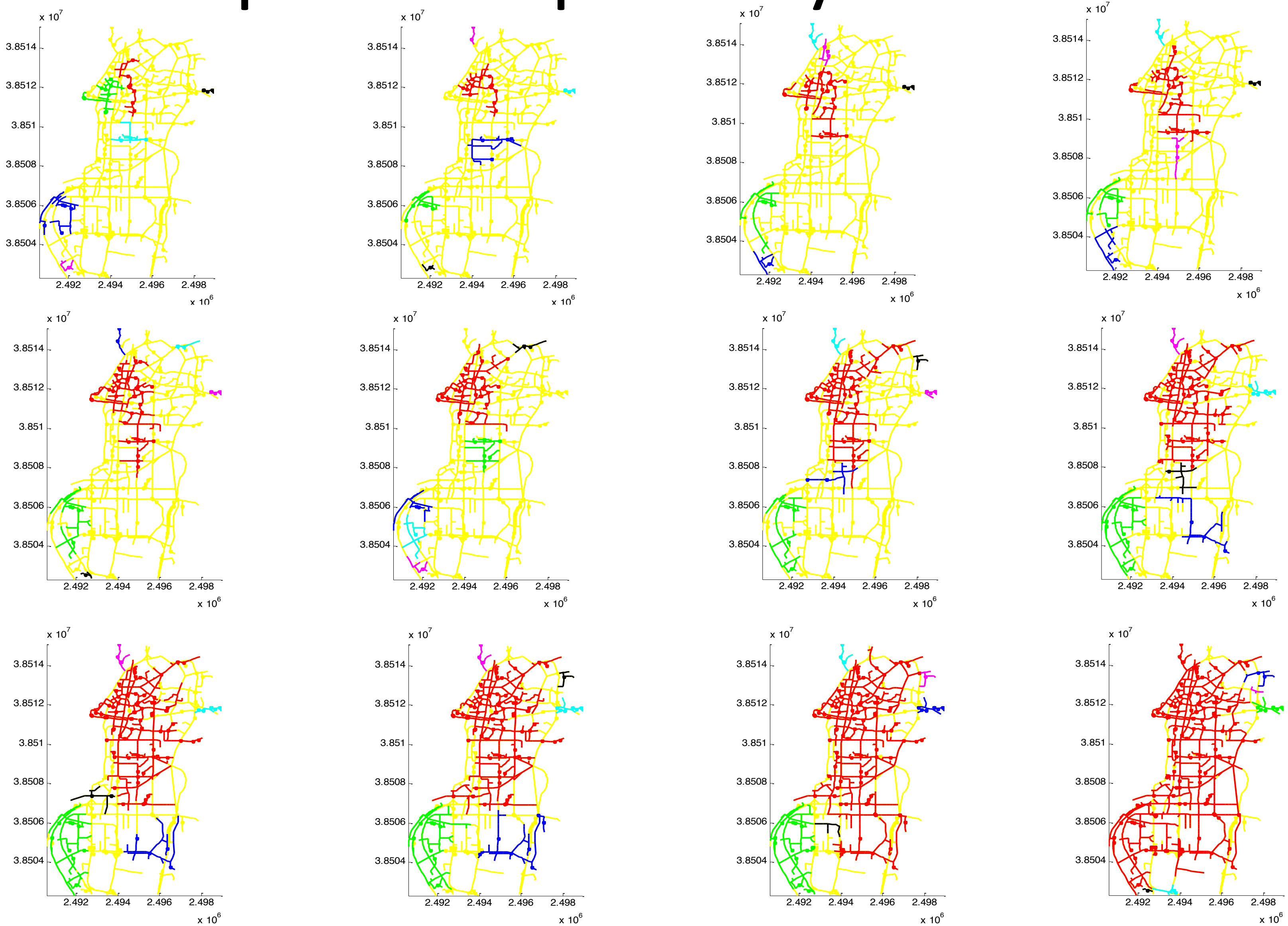
20000 taxis (25M points/day) 9000 links 12M population



Ongoing

Ji and Geroliminis (2013) – Ongoing

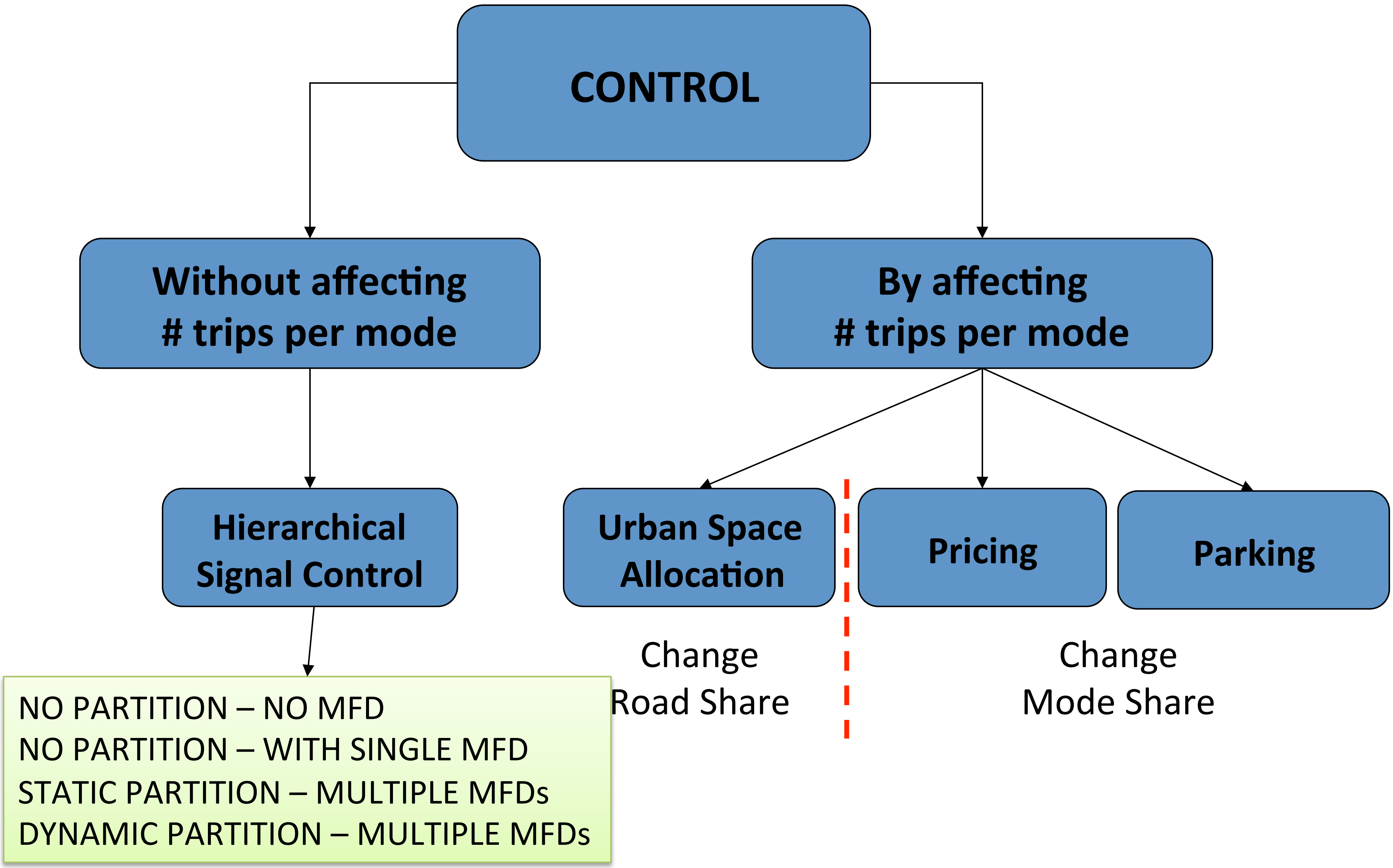
Spatiotemporal Dynamics



Small number of critical pockets of congestion

20000 taxis (30M points/day)
9000 links 12M population

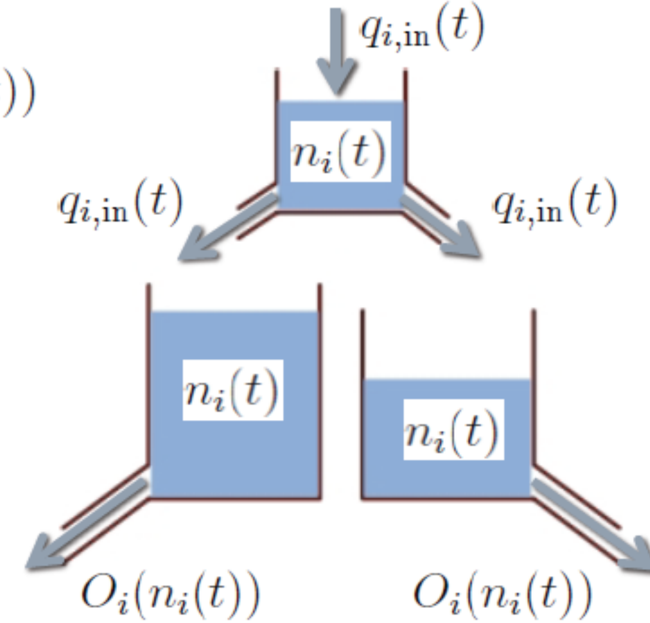
Smart Cities Management



Multivariable Feedback Regulators

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

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



- **Linear-quadratic control** (multivariable P-regulators)

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

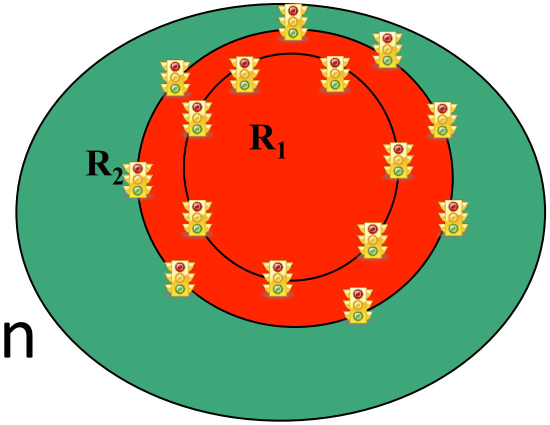
- **Linear-quadratic-integral control** (multivariable PI-regulators)

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

Aboudolas and Geroliminis (2013) – TR part B

Selection of perimeter

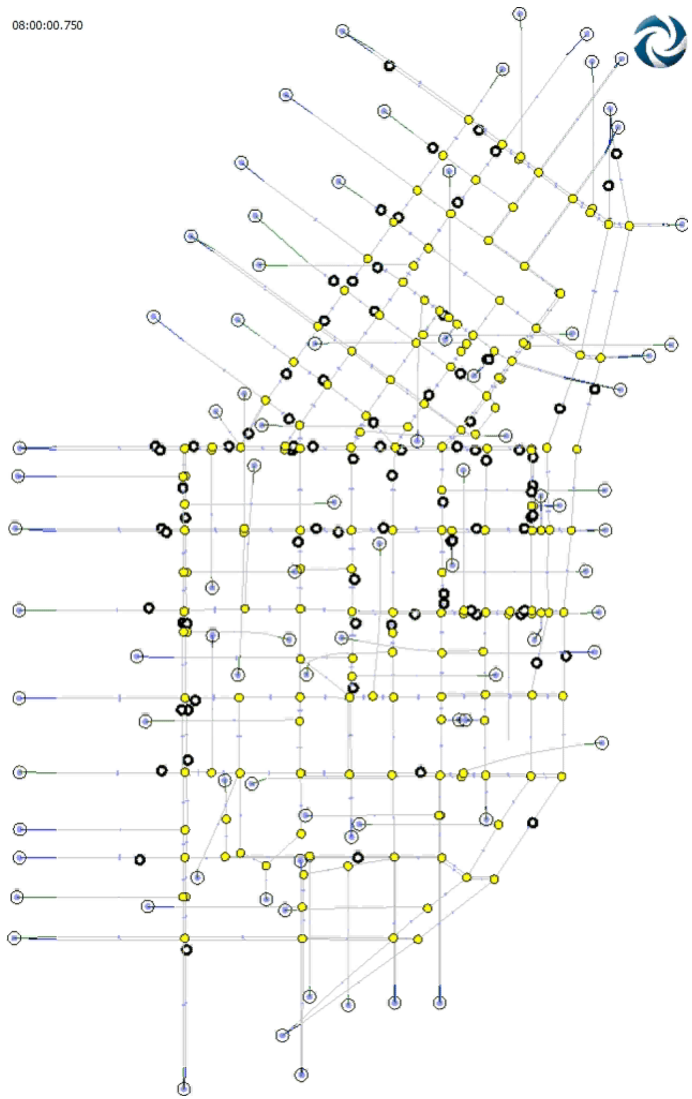
- Criteria
  - Partitioning (Region Homogeneity)
  - Critical traffic signals (underutilization of green)
  - Queue lengths propagation
  - Adaptivity



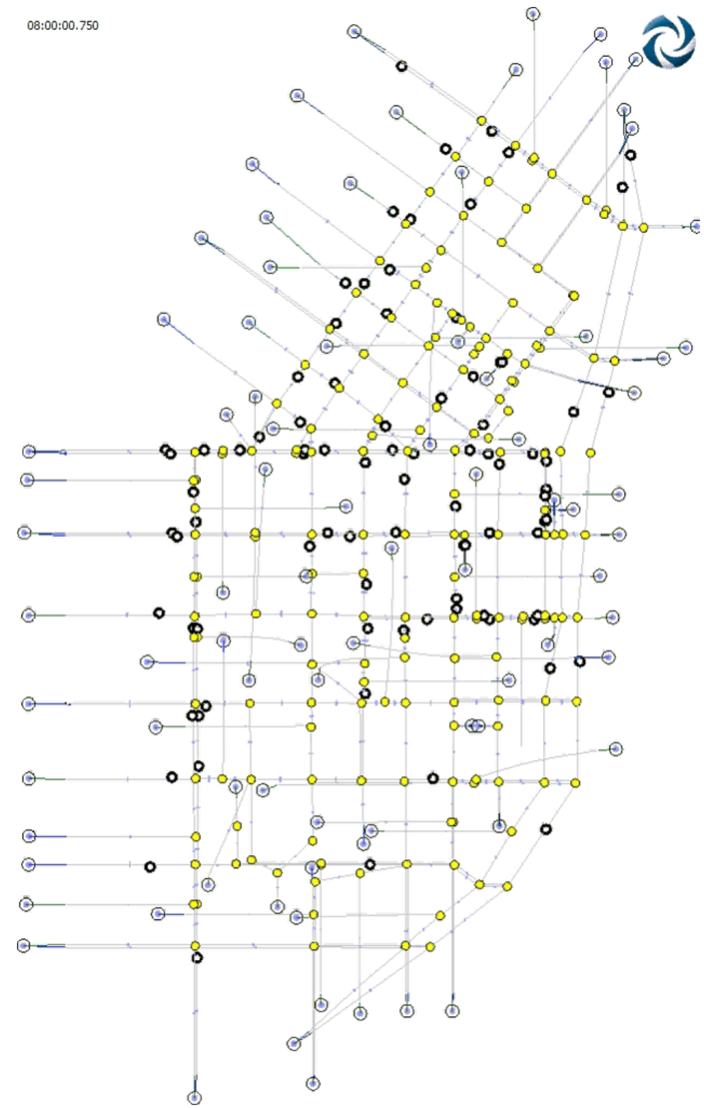
- Implementation
  - Queue length equalization
  - Equity

Feedback Multi-Boundary Control

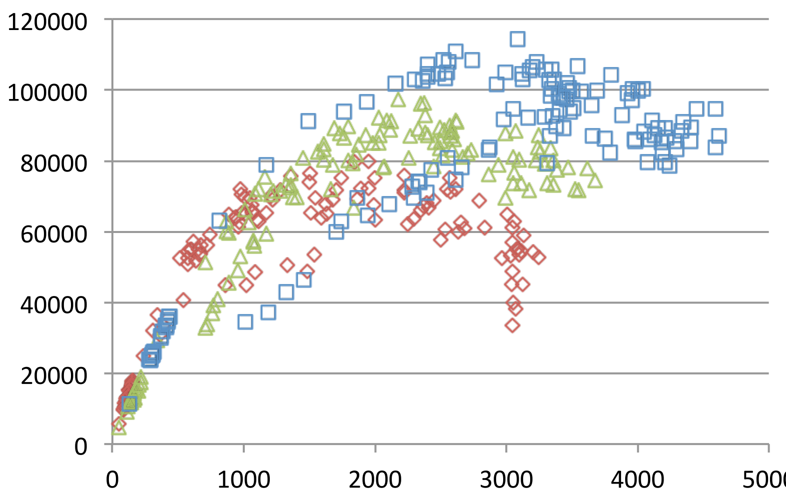
Pre-timed Traffic Control



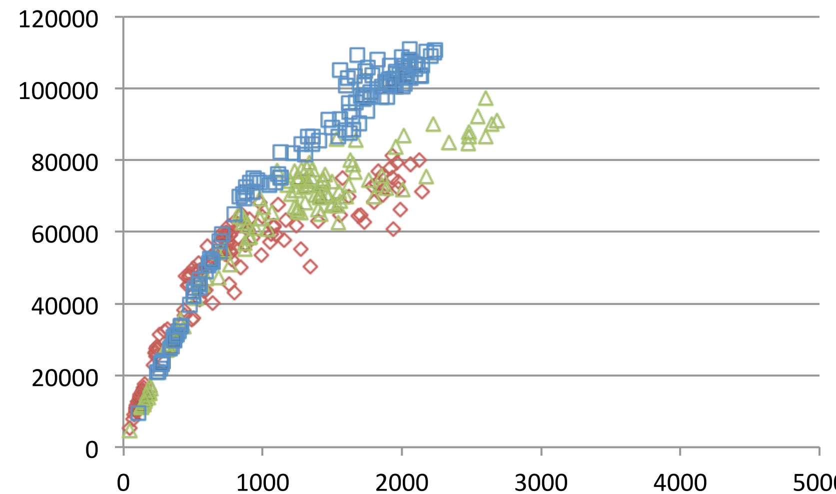
Smart Traffic Control



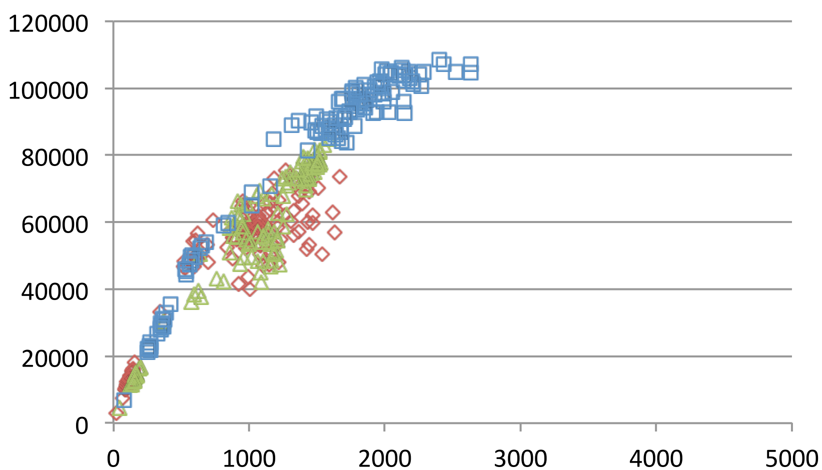
Comparison with Other Controllers



Pre-timed fixed control (PT)



Multiple MFDs perimeter + boundary controllers (NEW)



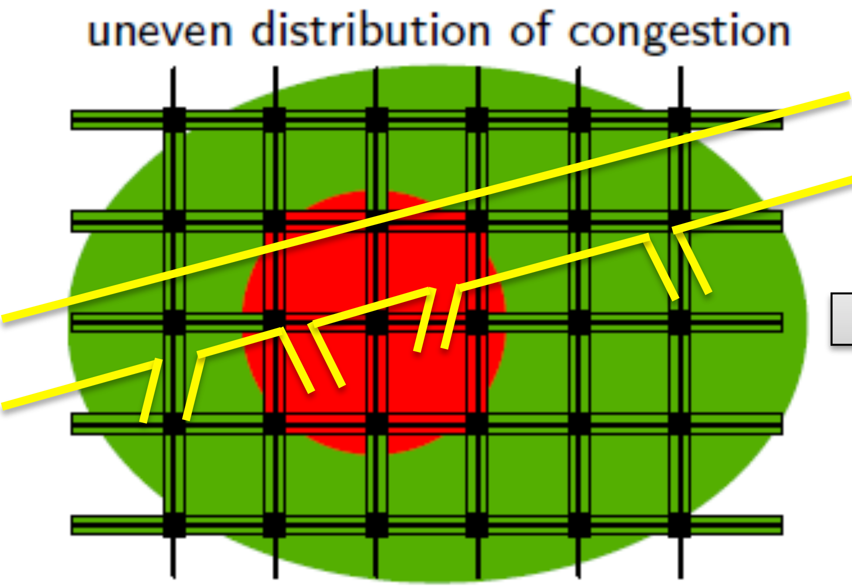
1 MFD perimeter controller (BBC)

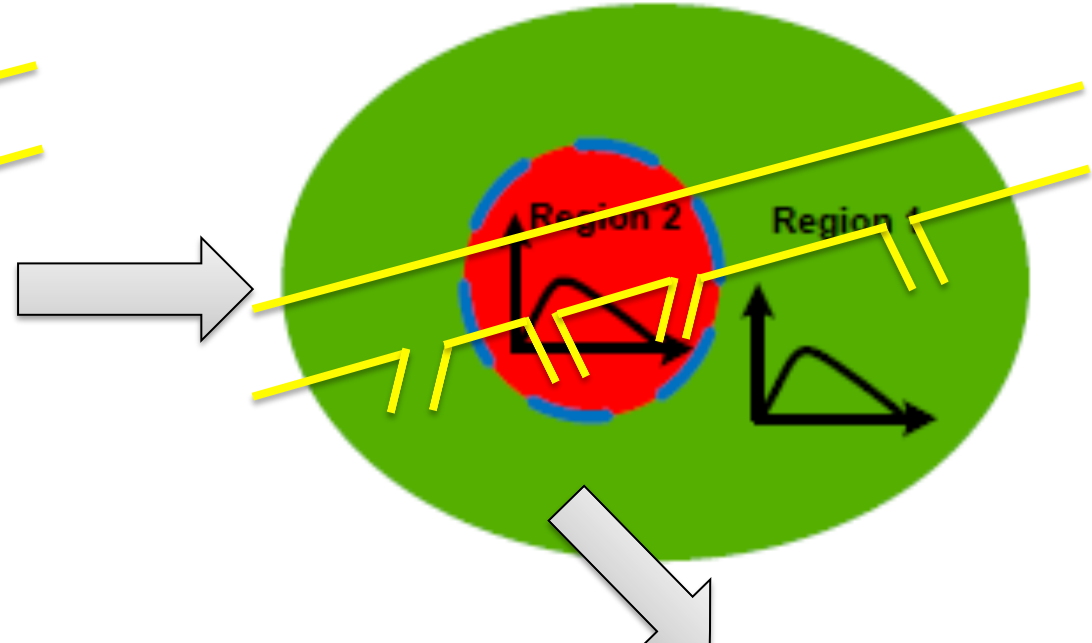
Improvements (total travel time)

- PT vs. NEW 45%
- NEW vs. BBC 12%

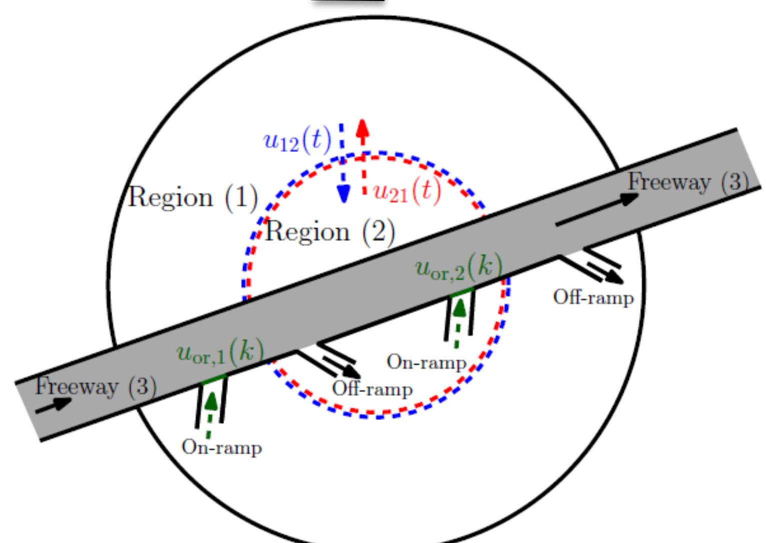
- Equitable distribution of queues
- Earlier activation of Control

Mixed Freeway-Arterial network





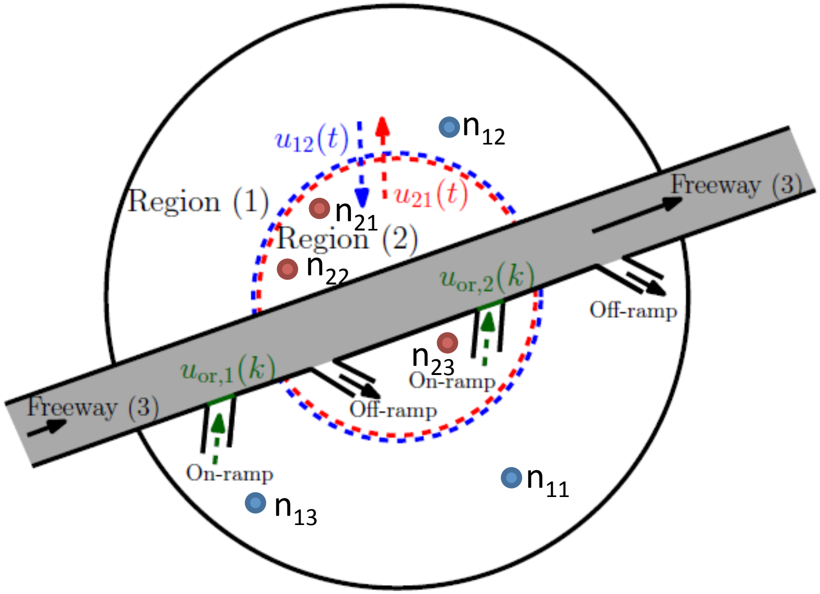
- **Problem Statement:**
  - Coordinated control of a mixed traffic network
  - The goal is to minimize the network total delay
  - A receding horizon framework (MPC) to solve the optimal control problem
- **Controllers are:**
  - <u>2 Ramp metering</u>
  - <u>2 Perimeter controllers</u>



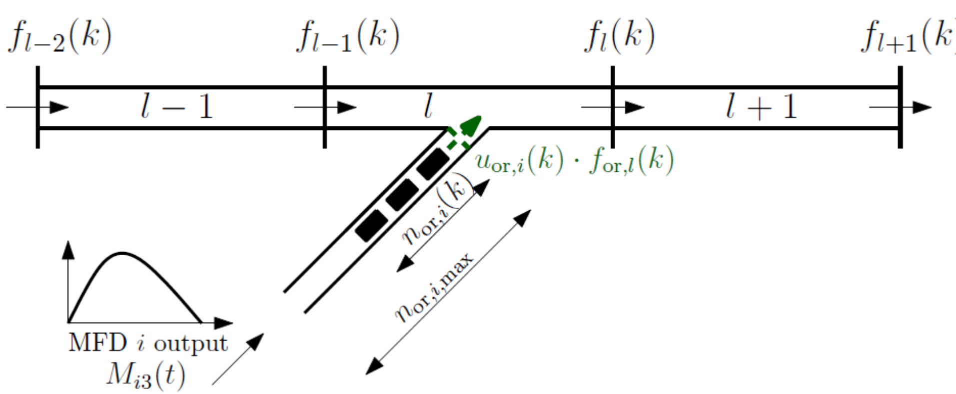
Haddad, Ramezani, Geroliminis (2012, 2013) – Trans. Res. Part B and IEEE Transactions on ITS

Problem Definition

- The urban regions are modeled with MFDs
- The traffic dynamics of the freeway are modeled with the cell transmission model (CTM)
- Dynamic trip route choice
- Time dependent O-Ds



O\ D	1	2	3
1	$q_{11}: 1 \to 1$ $q_{131}: 1 \to 3 \to 1$	$q_{12}: 1 \to 2$ $q_{132}: 1 \to 3 \to 2$	$q_{13}: 1 \to 3$ $q_{123}: 1 \to 2 \to 3$
2	$q_{21}: 2 \to 1$ $q_{231}: 2 \to 3 \to 1$	$q_{22}: 2 \to 2$	$q_{23}: 2 \to 3$ $q_{213}: 2 \to 1 \to 3$
3	$q_{31}: 3 \to 1$ $q_{321}: 3 \to 2 \to 1$	$q_{32}: 3 \to 2$ $q_{312}: 3 \to 1 \to 2$	$q_{33}: 3 \to 3$



Problem Formulation

$$J = \min_{\substack{u_{12}(t),u_{21}(t)\\ u_{or,1}(k),u_{or,2}(k)}} \int_{t_0}^{t_f}[n_1(t)+n_2(t)]dt + \sum_{k=0}^{K-1}\sum_{l=1}^{L} x_l(k)$$

- $M_{ij} = \frac{n_{ij}}{n_i} \times G_i(n_i(t))$

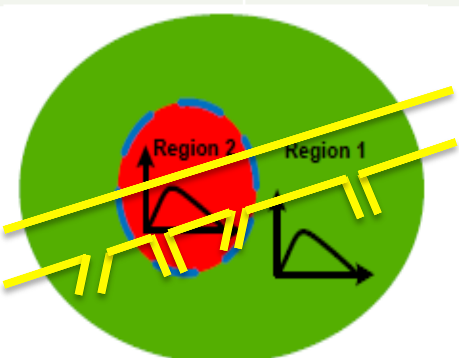
Subject to:

- $\frac{dn_{11}(t)}{dt} = \frac{\hat{q}_{321}(t)+q_{23}(t)}{\hat{q}_{321}(t)+q_{213}(t)+q_{21}(t)} u_{21}(t).M_{21}(t) + q_{11}(t) + \hat{q}_{231}(t) + \hat{q}_{31}(t) - M_{11}(t)$
- $\frac{dn_{12}(t)}{dt} = q_{12}(t) + q_{123}(t) + \hat{q}_{312}(t) - u_{12}(t).M_{12}(t)$
- $\frac{dn_{13}(t)}{dt} = \frac{q_{213}(t)}{\hat{q}_{321}(t)+q_{213}(t)+q_{21}(t)} u_{21}(t).M_{21}(t) + q_{13}(t) + q_{131}(t) + q_{132}(t) - \min(M_{13}(t), C_{or,1}(t))$
- $\frac{dn_{21}(t)}{dt} = q_{21}(t) + q_{213}(t) + \hat{q}_{321}(t) - u_{21}(t).M_{21}(t)$
- $\frac{dn_{22}(t)}{dt} = \frac{\hat{q}_{312}(t)+q_{12}(t)}{\hat{q}_{312}(t)+q_{12}(t)+q_{123}(t)} u_{12}(t).M_{12}(t) + q_{22}(t) + \hat{q}_{132}(t) + \hat{q}_{32}(t) - M_{22}(t)$
- $\frac{dn_{23}(t)}{dt} = \frac{q_{123}(t)}{\hat{q}_{312}(t)+q_{12}(t)+q_{123}(t)} u_{12}(t).M_{12}(t) + q_{23}(t) + q_{231}(t) - \min(M_{23}(t), C_{or,2}(t))$
- $C_{or,i}(t) = (n_{or,i,max} - n_{or,i}(k))/T_k$; available flow capacity in the on-ramp queue
- $u_{min} \le u_{12}(t), u_{21}(t) \le u_{max}$; $u_{min} \le u_{or,1}(k), u_{or,2}(k) \le u_{max}$
- $0 \le n_1(t) \le n_{1,jam}$; $n_1(t) = n_{11}(t) + n_{12}(t) + n_{13}(t)$
- $0 \le n_2(t) \le n_{2,jam}$; $n_2(t) = n_{21}(t) + n_{22}(t) + n_{23}(t)$
- and CTM formulas

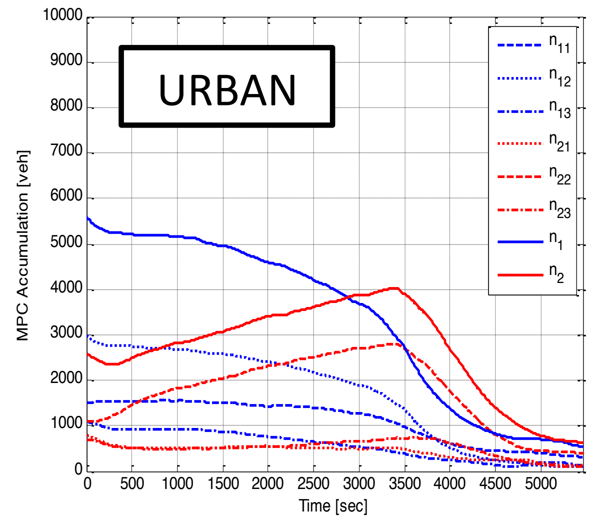
Results

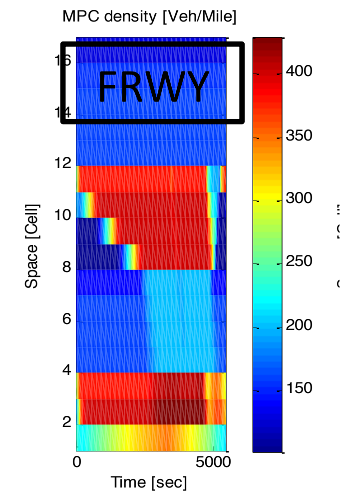
Delay (veh.sec X 10^6)

	ALINEA Q	Urban MPC + ALINEA Q	FULL MPC
Region 1	438	262	196
Region 2	97	160	143
Freeway	172	189	218
On-Ramp 1	13	15	8
On-Ramp 2	16	16	16
Network	**736**	**642**	**581**

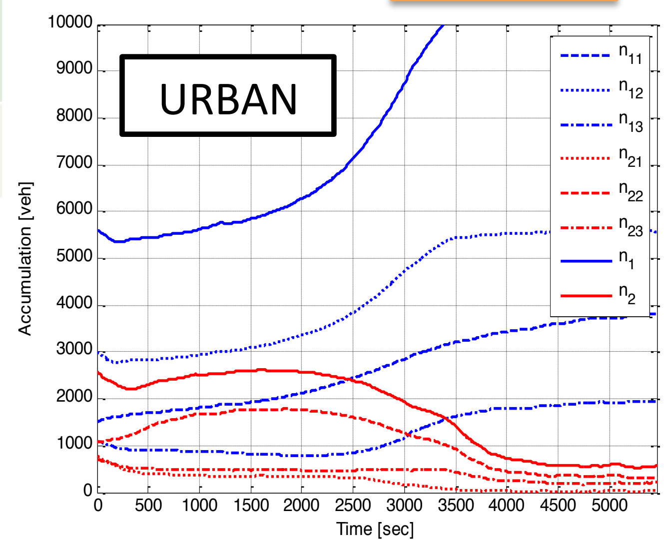


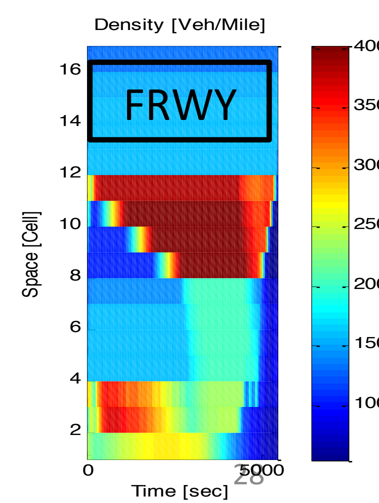
FULL MPC





ALINEA Q





Multimodal networks

- In urban networks, buses usually share the same network with the other vehicles.
- Movement Conflicts in multi-modal urban traffic systems
- Bus stops affect the system like variable red signals in a single lane (instead of blocking all lanes).
- Increasing bus frequency decreases the flow of vehicles but can increase the flow of passengers.

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

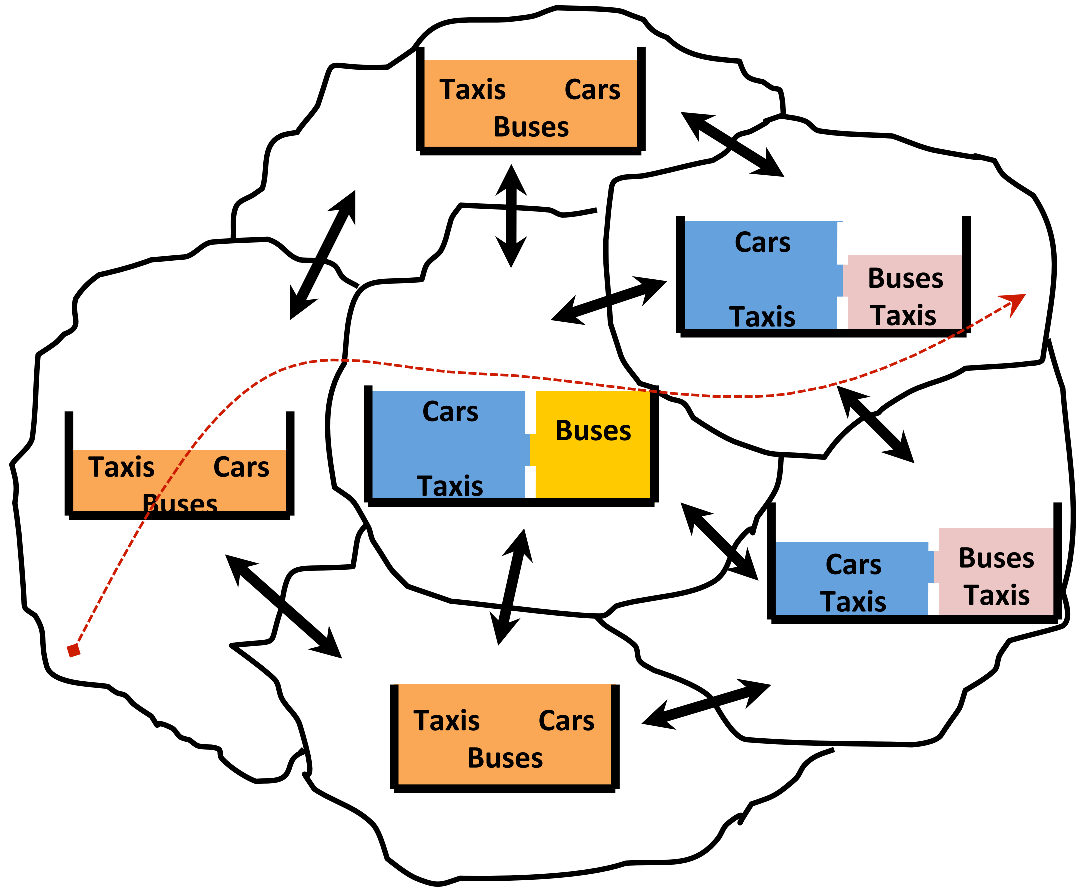
- **Competing modes**
- **Parking**
- **Pax vs. veh throughput**

MULTIMODAL CITIES

Multimodal multi-reservoir system

Challenges

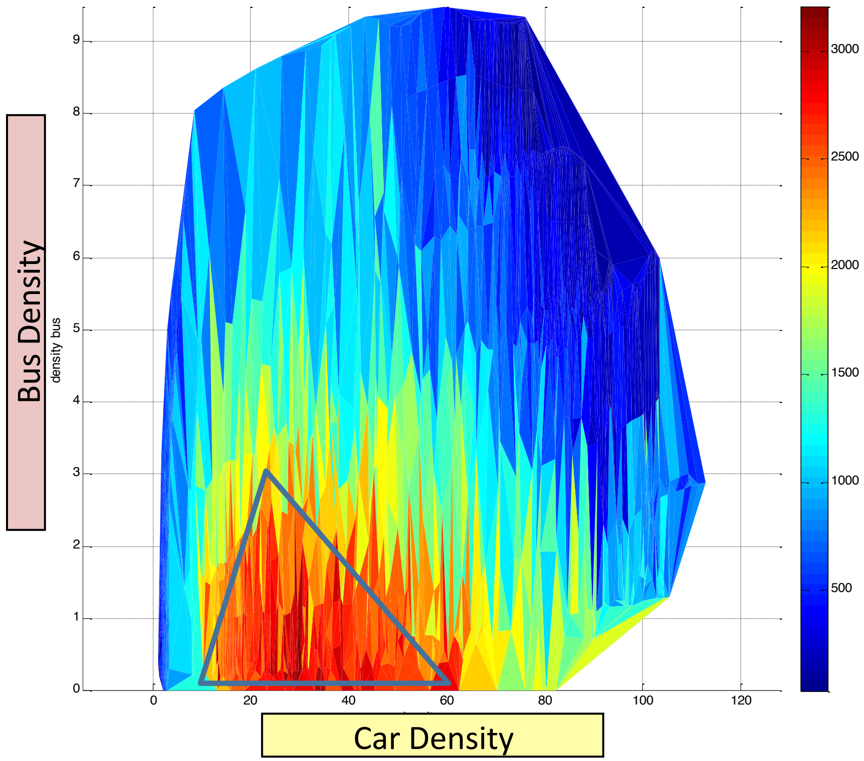
- Model: Dynamics
- Monitor: Existence + Observability
- Control: Redistribution of urban space between modes
- Implementation



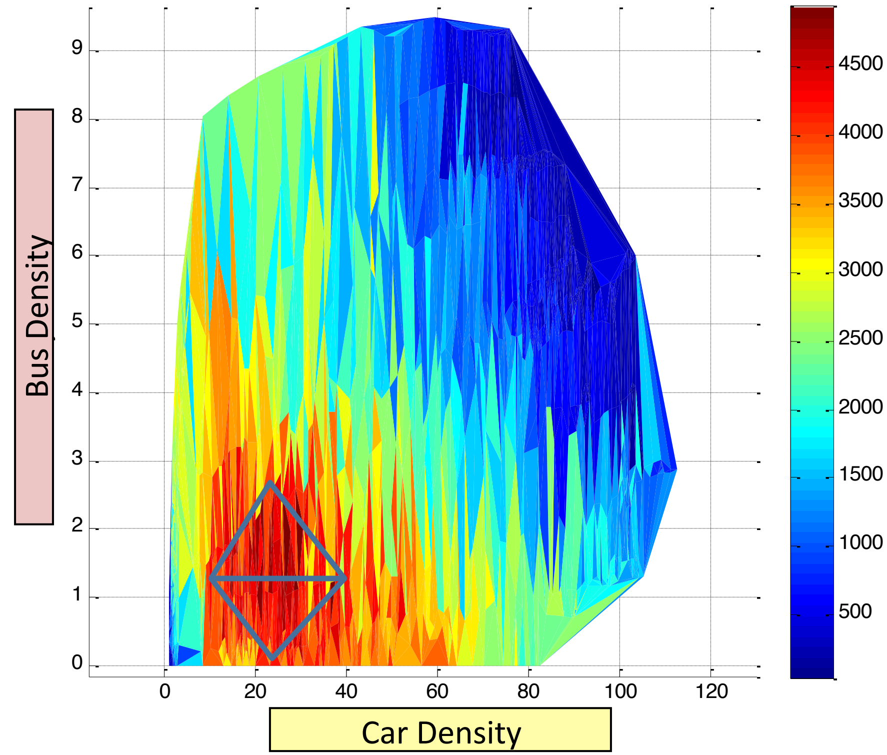
Geroliminis and Boyaci (2012) – Tr. Res. Part B

Zheng and Geroliminis (2013) ISTTT20

Two-mode 3-D MFD (mixed traffic)



VEHICULAR FLOW

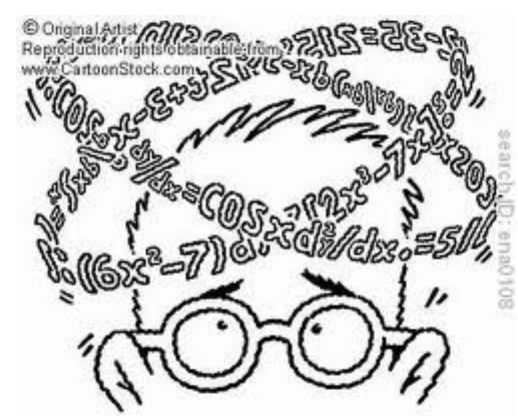


PASSENGER FLOW

Simulated data – Downtown SF

Challenging Research Questions

- Control of more complex city structures with route choice
- Field test Implementations
- Congestion Spreading in 2D urban networks
- Travel time reliability and Control
- Multimodal city networks (People + Goods)
- Smart shared-use mobility




DISCUSSION