20th International Symposium on Transportation and Traffic Theory, Noordwijk, the Netherlands, 16-19 July 2013

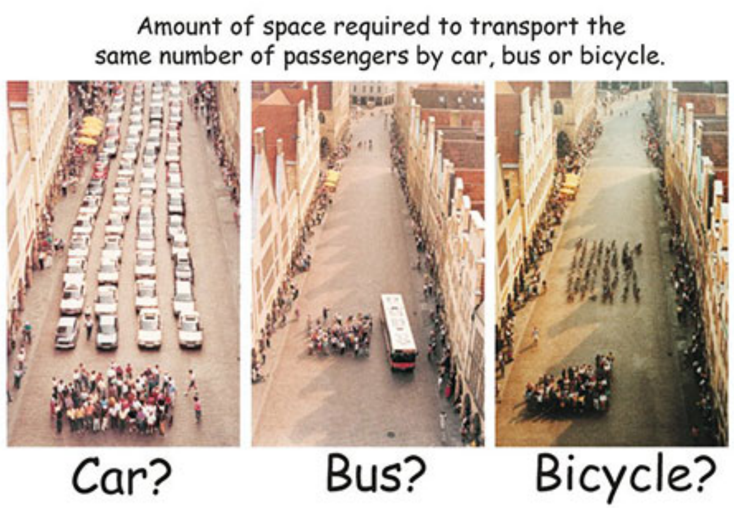
On the distribution of urban road space for multimodal congested networks

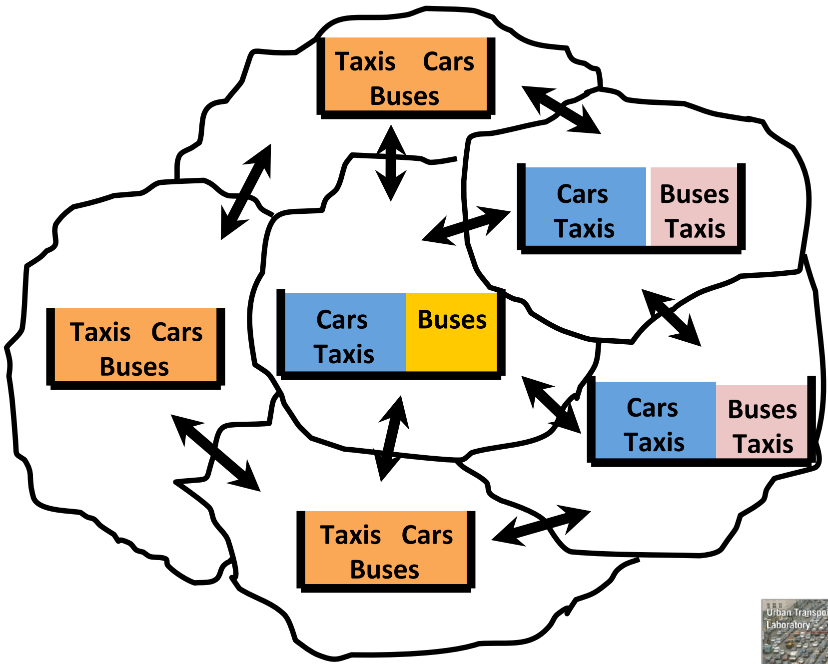
Nan Zheng and Nikolas Geroliminis

Urban Transportation Systems Laboratory (LUTS),
École Polytechnique Fédérale de Lausanne (EPFL)

Highlights

- Understand multimodal interactions at the network level
- Model the aggregated dynamics of a multimodal system
- Integrate traffic dynamics in planning and design
- Optimize system performance with space distribution and pricing

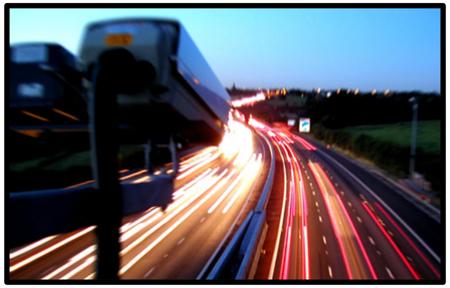


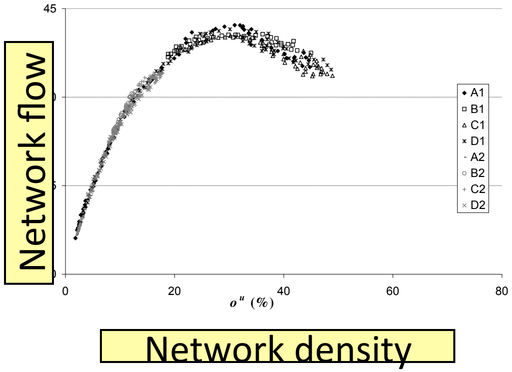


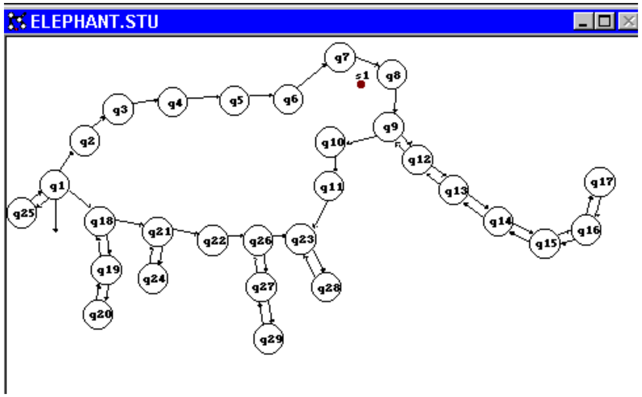
Why Macro?

- Humans make choices of routes, destinations and driving behavior (unpredictability)
- Not a clear distinction between free-flow and congested traffic states (complexity)
- Need for real-time hierarchical traffic management schemes (efficiency)

Solution (?):
A network based aggregated approach







"With four parameters I can fit an elephant". JOHN VON NEUMANN

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.

$$\min_{\boldsymbol{\pi}_i(\boldsymbol{t})} Z = \sum_{t,i,m} \mathrm{PHT}_{t,i,m}\left(\boldsymbol{\pi}_i(\boldsymbol{t})\right)$$

Performance Measures

Vehicle Hours Traveled
Vehicle Kilometers Traveled

Passenger Hours Traveled
Passenger Kilometers Traveled

→

Mobility (Accessibility)

Emissions (Environ. Impacts)

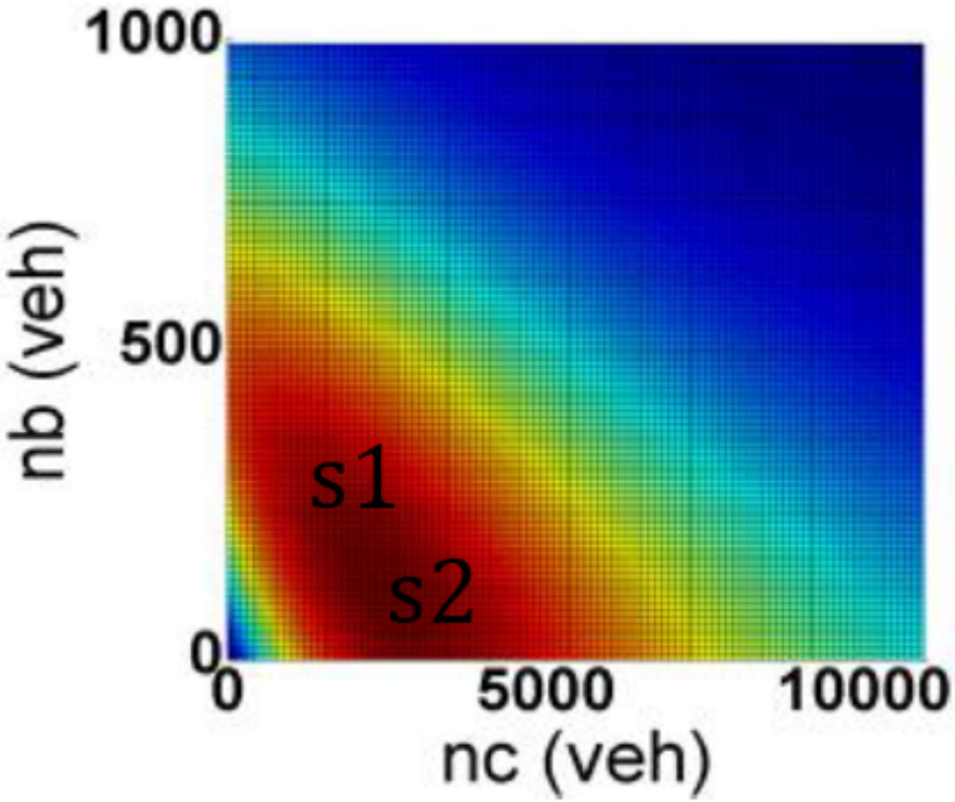
Costs (Users, Providers, etc.)

Road Space Used

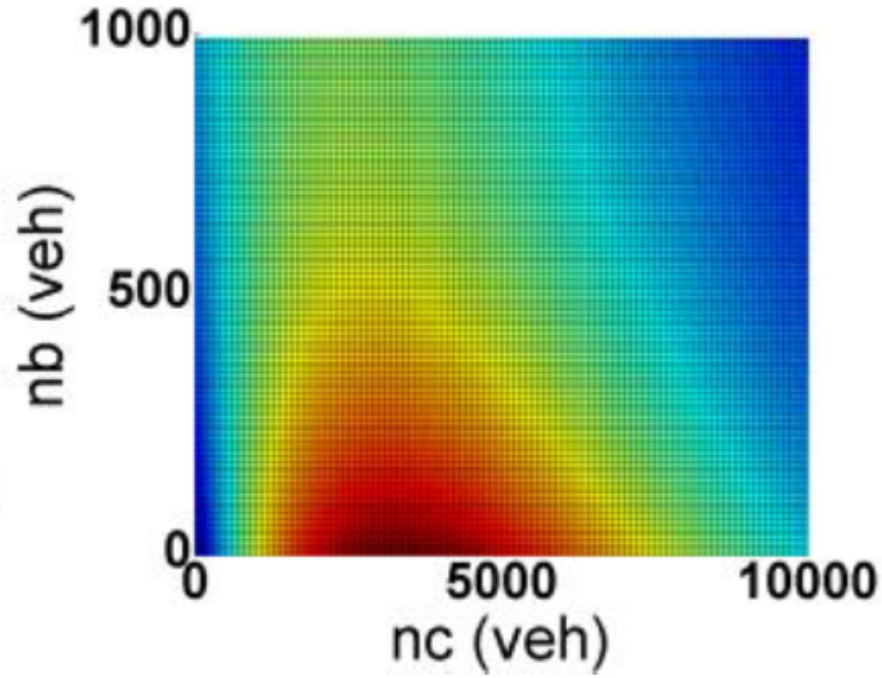
- **Competing modes**
- **Parking**
- **Pax vs. veh throughput**

MULTIMODAL CITIES

Motivation – A multi-modal MFD



PASSENGER MFD

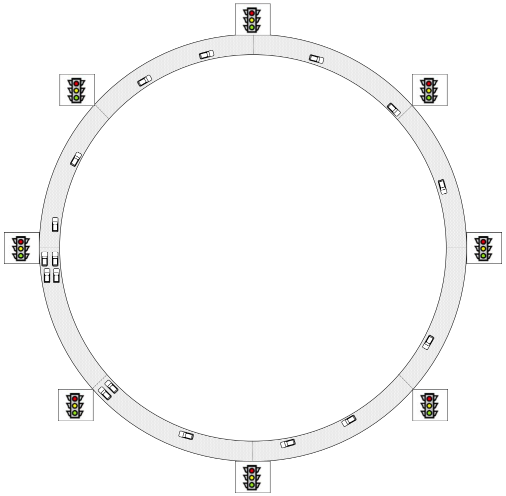


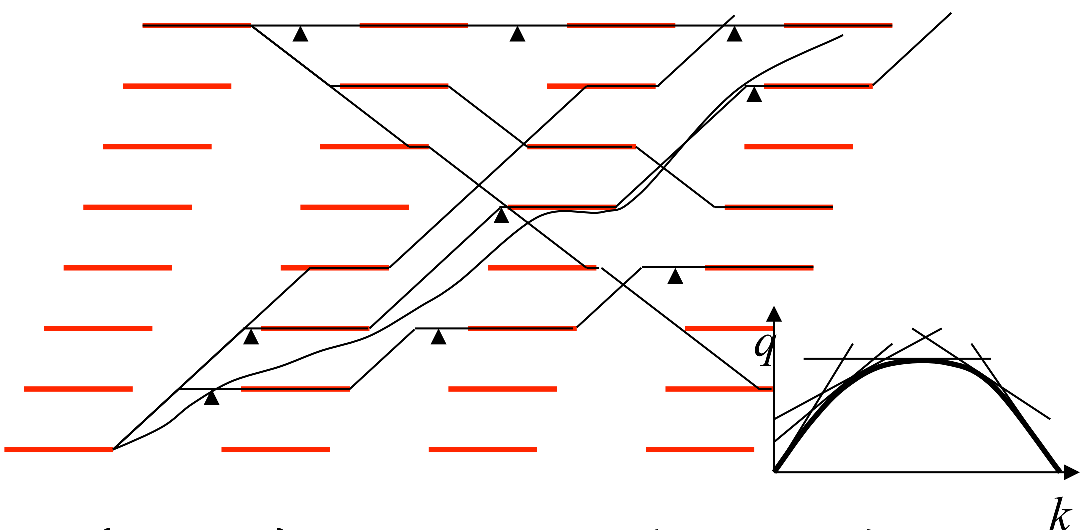
VEHICLE MFD

Simulated data – Downtown San Francisco

Zheng et al. (2013) – Ongoing

Intro to Variational Theory



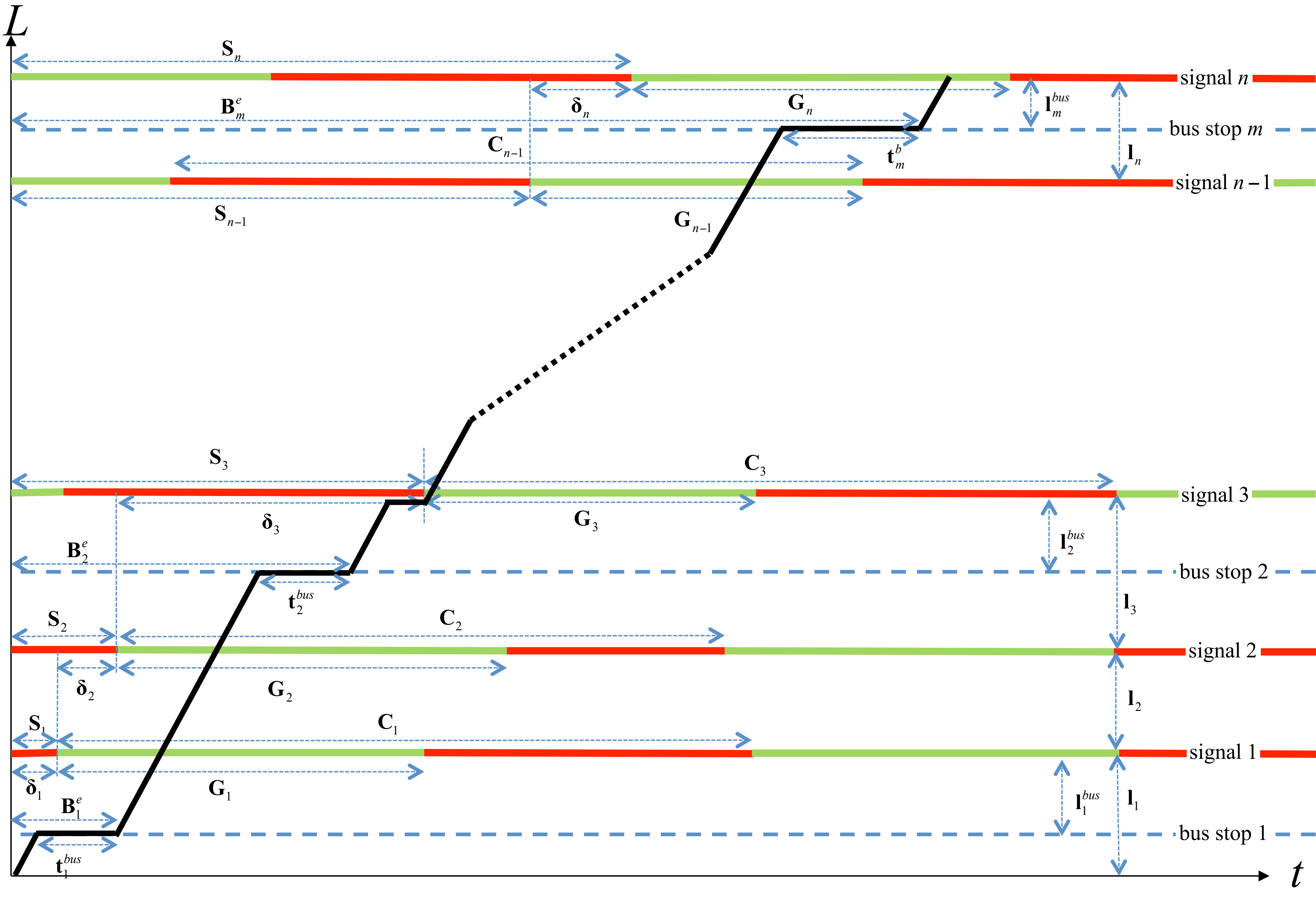


$$q = \inf_{u} \left\{ ku + R(u) \right\} \qquad R(u) = \lim_{t_0 \to \infty} \inf_{\mathcal{P}} \left\{ \Delta(\mathcal{P}) : u_{\mathcal{P}} = u \right\} / t_0$$

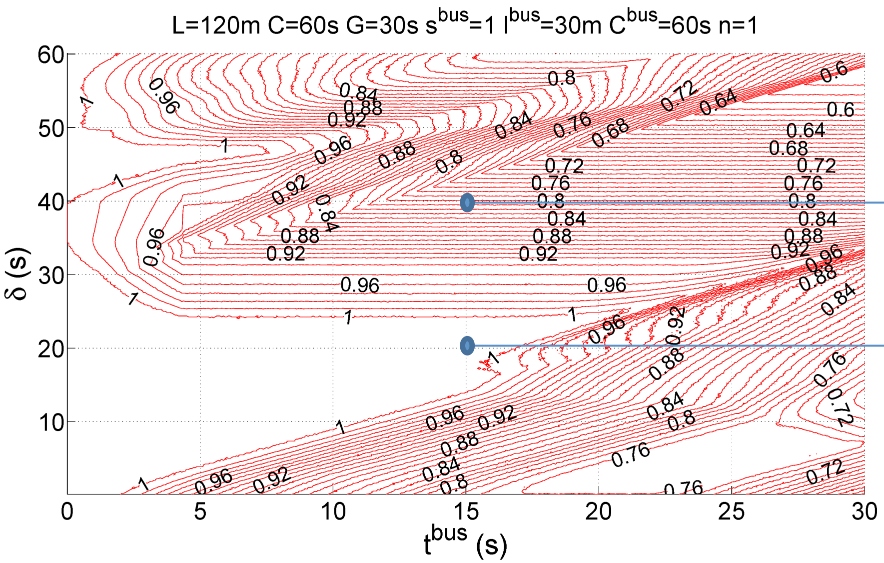
- VT estimates exactly the MFD for a ring with no turns.
- For networks, this estimation is an upper bound
- Results from real cases show that this is almost tight for homogeneous distribution of congestion.

Daganzo and Geroliminis (2008) – TR part B
Geroliminis and Boyaci (2012) – TR part B
Leclercq and Geroliminis (2013) - ISTTT

Variational Theory for multimodal networks

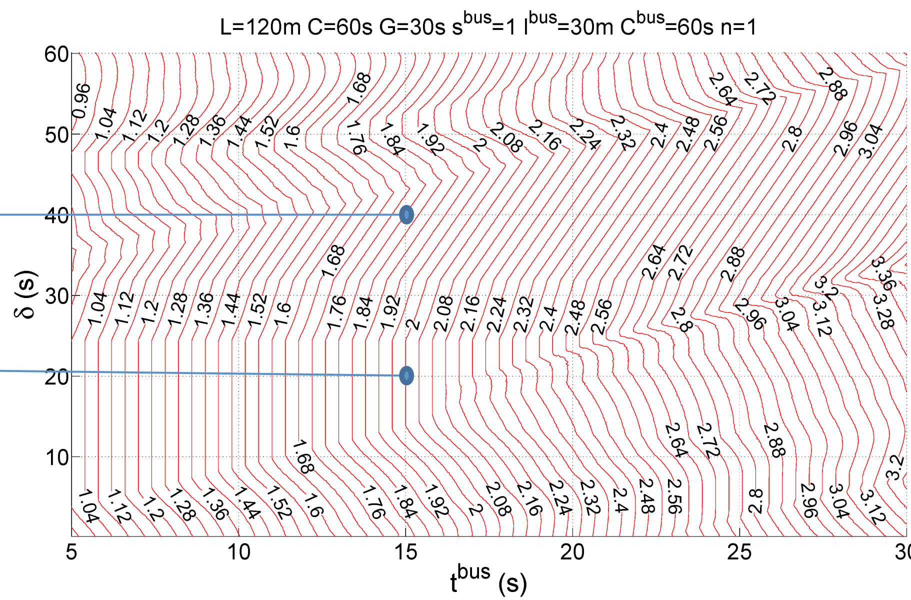


The effect of dwell times in network capacity



C=60s, G=30s, δ=40, L=200m
l^{bus}=30m, C^{bus}=60s, n=1

C=60, G=30, δ=20, L=200
l^{bus}=30, C^{bus}=60, n=1

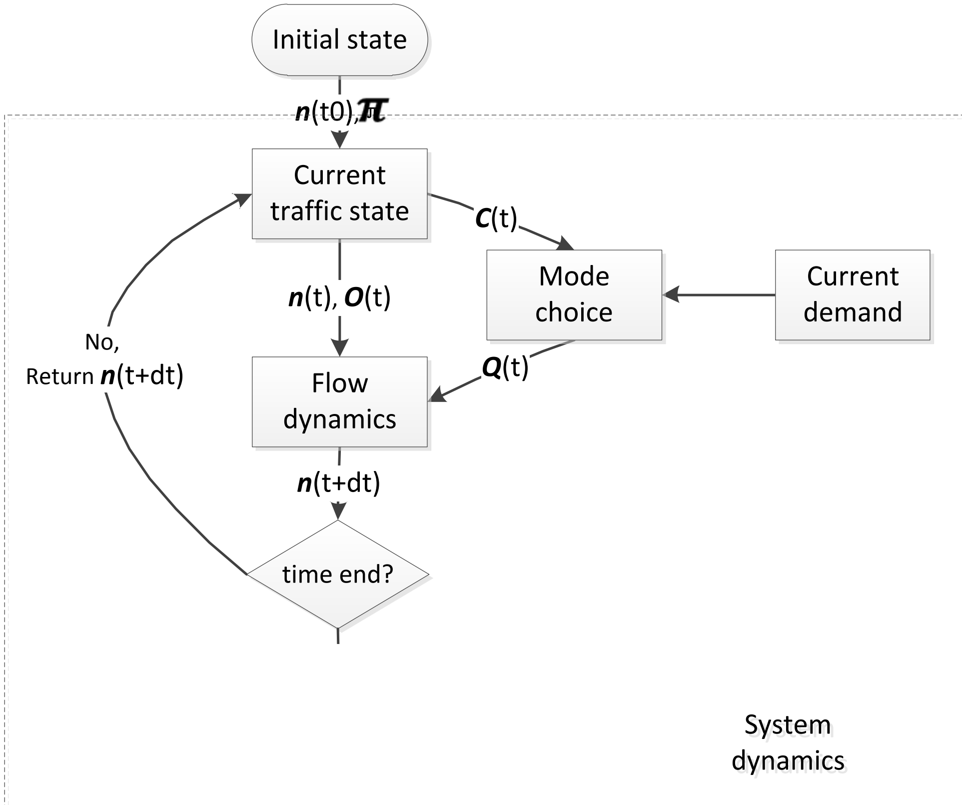


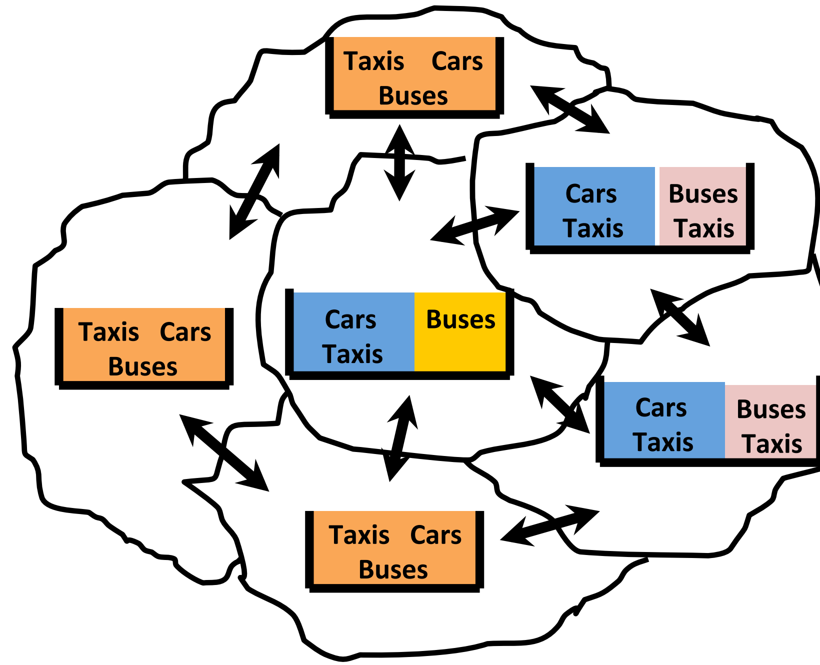
C=60, G=30, δ=40, L=200
l^{bus}=30, C^{bus}=60, n=1

C=60, G=30, δ=20, L=200
l^{bus}=30, C^{bus}=60, n=1

Geroliminis and Boyaci (2012) – Working paper

Methodology - General representation of a multimodal system





$\boldsymbol{\pi}$: space share allocation

$\boldsymbol{n}(\boldsymbol{t})$: accumulation of vehicles (all modes) in the regions at time t

$O(\boldsymbol{t})$: transfer flows (all modes) in the regions at time t

$Q(\boldsymbol{t})$: generated demand per mode in the regions at time t

$C(\boldsymbol{t})$: cost of travel in the regions at time t

Methodology - Traffic flow dynamics (1)

- Mass conservation of vehicles (discretized):

$$n_i^{kc}(t+1) = n_i^{kc}(t) + \frac{Q_i^{kc}(t+1)}{ob_i^c} - \sum_{j=1}^{N} O_{i\to j}^{kc}(t) + \sum_{l=1}^{N} O_{l\to i}^{kc}(t), \qquad \text{CAR}$$

$$n_i^{kb}(t+1) = n_i^{kb}(t) - \sum_{j=1}^{N} O_{i\to j}^{kb}(t) + \sum_{l=1}^{N} O_{l\to i}^{kb}(t), \qquad \text{BUS}$$

$n_i^{km}(t)$: accumulation of mode *m* in region *i* with next destination region *k* at time *t*
$O_{i\to j}^{km}(t)$: transfer flow of mode *m* from region *i* to *j* with final destination *k* at time *t*
$Q_i^{km}(t)$: demand generated *k* at time *t* in region *i* with next destination region *k*, choosing mode *m*
ob_i^c : average number of passengers per car in region *i*

Methodology - Traffic flow dynamics (2)

- Conservation of passengers:

$$OB_i^{kb}(t+1) = OB_i^{kb}(t) + Q_i^{kb}(t+1) - \sum_{j \neq i}^{N} O_{i \to j}^{kb}(t) \cdot ob_i^{kb}(t) +$$

$$\sum_{l=1}^{N} O_{l \to i}^{kb}(t) \cdot ob_l^{kb}(t) - b_i^k \cdot OB_i^{kb}(t) \cdot (1 - (1 - \theta_i)^z)$$

$OB_i^{kb}(t)$: the number of bus on-board passengers currently in region i with final destination k
$ob_i^{kb}(t)$: the average number of on-board passengers per bus from region i to k
b_i^k : binary variable indicating if reaching destination, b_i^k = 1 for i= k and 0 otherwise
θ_i : probablity of reaching destination
z : number of stops that a bus travels during interval t

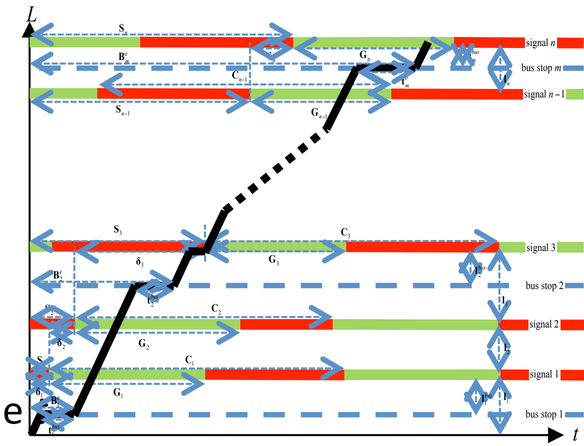
θ_i is a Bernoulli trial repeated z times, $\theta_i = \left(\frac{\bar{L}'_{ib}}{s_i}\right)^{-1}$, where $\bar{L}'_{ib}$ is the trip length s_i and is the bus station spacing

Methodology – Multimodal travel time estimation

- Speed estimation for single-mode only region: $V_i^m(t) \stackrel{\text{def}}{=} \dfrac{P_i^m(t)}{n_i^m(t)} = \dfrac{O_i^m(t) \cdot \bar{L}_{im}}{n_i^m(t)}$

- Speed estimation for mixed mode region: $V_i^b(t) = V_i^c(t) \cdot \alpha_i^b(t), \;\; \alpha_i^b(t) = \dfrac{TT_i^b(t)}{TT_i^b(t) \; + TT_d^b(t)}$

- Travel time estimation: $TT_i^m(t) = \dfrac{\bar{L}_{im}}{V_i^m(t)}$



$V_i^m(t)$: travel speed of mode *m* in region *i*
$P_i^m(t)$: travel production of mode *m* in region *i*
$O_i^m(t)$: Outflow of mode *m* from region *i* (given by MFD)
$\bar{L}_{im}$: average trip length of mode *m* in region *i*
$TT_i^m(t)$: travel time of mode *m* in region *i* without scheduled stops at time
$TT_d^b(t)$: average time spent by bus dwelling for passengers at time *t*

- Assumptions:

Buses travel with the same speed of cars, if not dwelling for passengers

Methodology – Mode choice

- Utility of traveling by each mode:

$$U_i^{kc}(t) = -\sum_{j\in\{S_i^k\}} \left(TT_j^c(t) + C_j^c(t)\right),\ U_i^{kb}(t) = -\sum_{j\in\{S_i^k\}} \left(TT_j^b(t) + D_j^b(t)\right)$$

- Mode choice calculation:

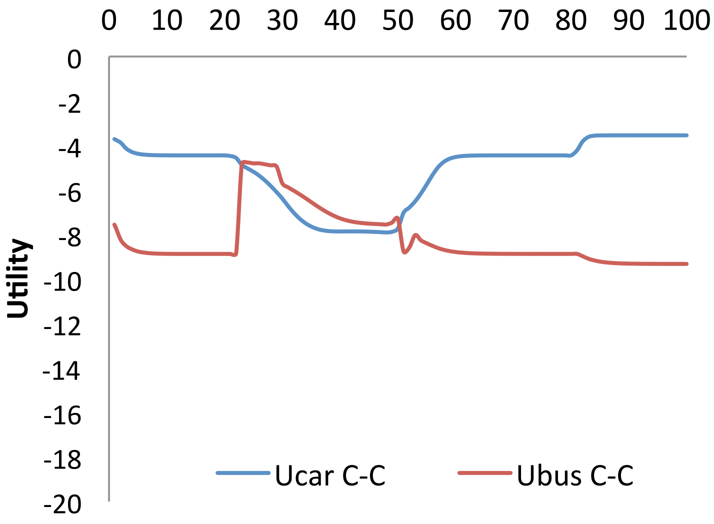
$$p_i^{kb}(t+1) = p_i^{kb}(t) + \beta_1 \cdot \Delta U_i^k(t) + \beta_2 \cdot \left(\Delta U_i^k(t) - \Delta U_i^k(t-1)\right)$$

$U_i^{km}(t)$: Utility of traveling by mode *m* from region i to *k* at time *t*

$C_j^c(t)$: cost other than travel time for using cars in region *j* at time *t*

$D_j^b(t)$: discomfort for using buses in region *j* at time *t*

$p_i^{kb}(t)$: percentage of the demand generated at time *t* in region i choosing mode bus



Methodology – Optimization framework

- System performance measure:

$$PHT(\boldsymbol{\pi}) = \sum_{t}\sum_{i}\sum_{k}\left(n_i^{kc}(t)\cdot ob_j^{kc} + OB_i^{kb}(t)\right)\cdot T$$

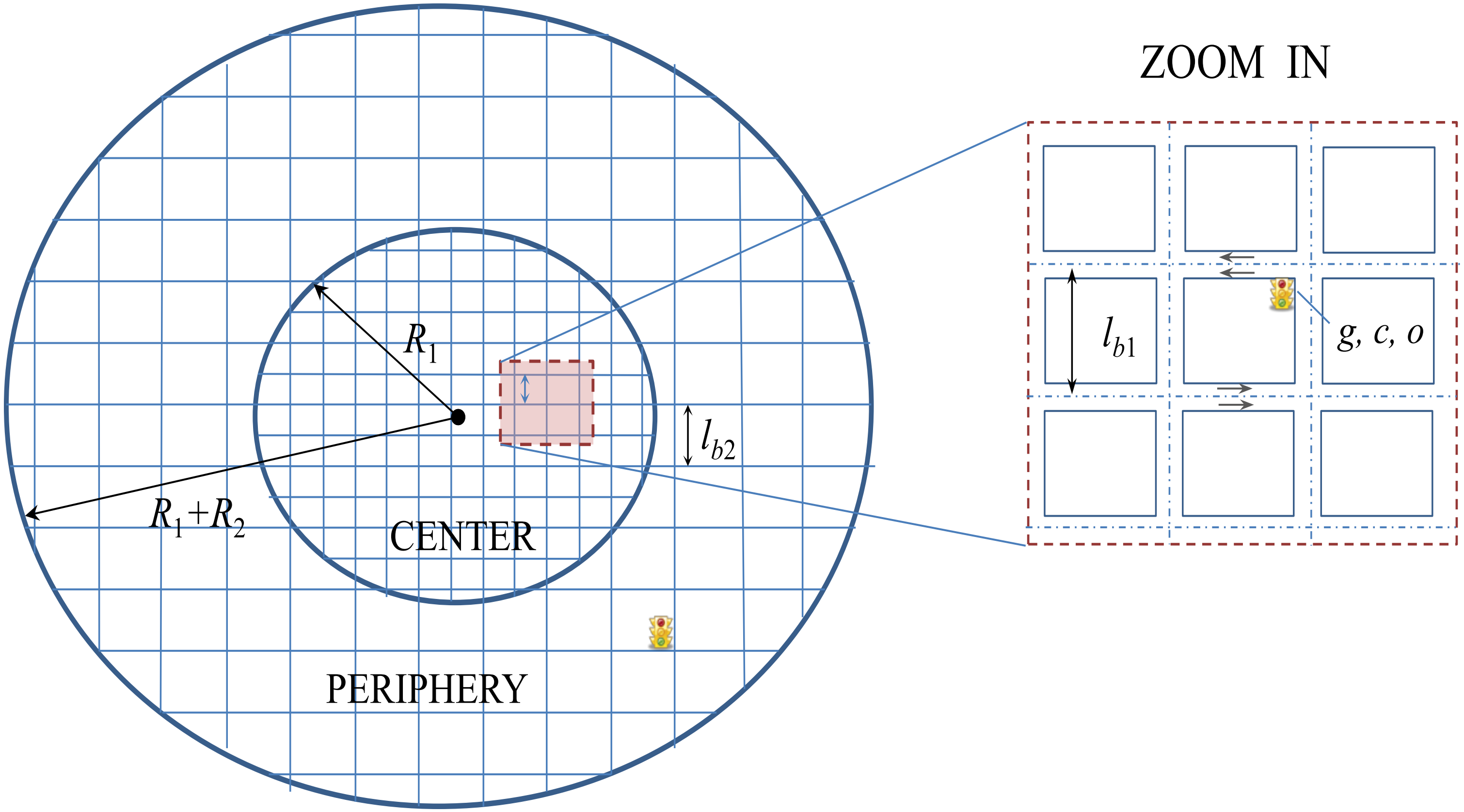
- Objective function:

$$\min_{\boldsymbol{\pi_i}(\boldsymbol{t})} Z = \sum_{t,i,m} PHT_{t,i,m}\left(\boldsymbol{\pi_i}(\boldsymbol{t})\right)$$

$\boldsymbol{\pi_i}(\boldsymbol{t})$: the space distribution plan for region i at time t

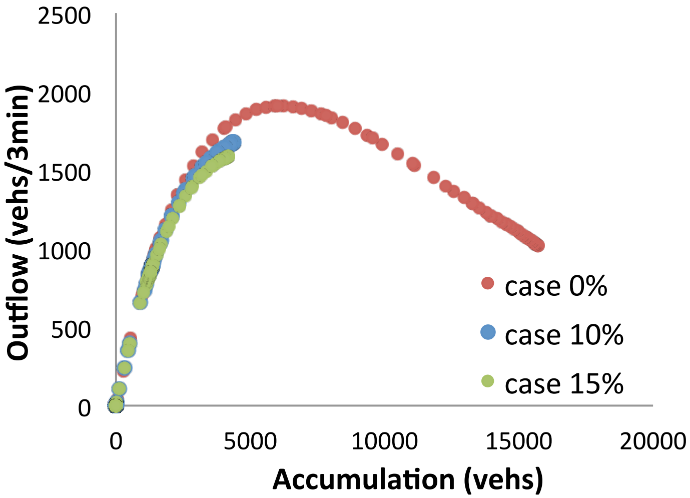
- Optimization algorithm: Lagrangian SQP with multiple initial search

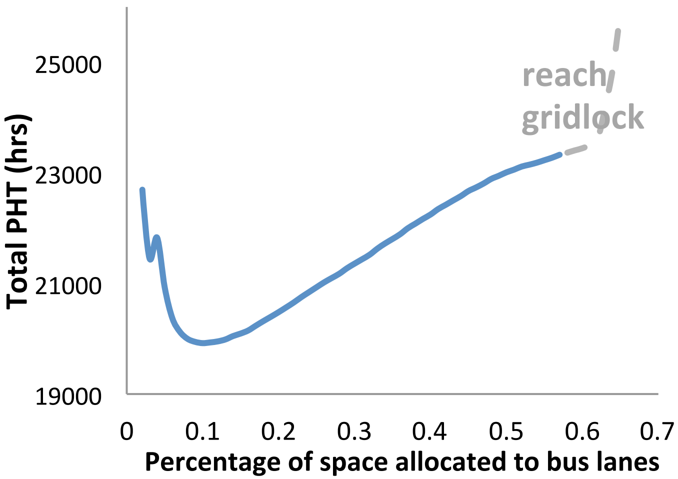
Case study set-up



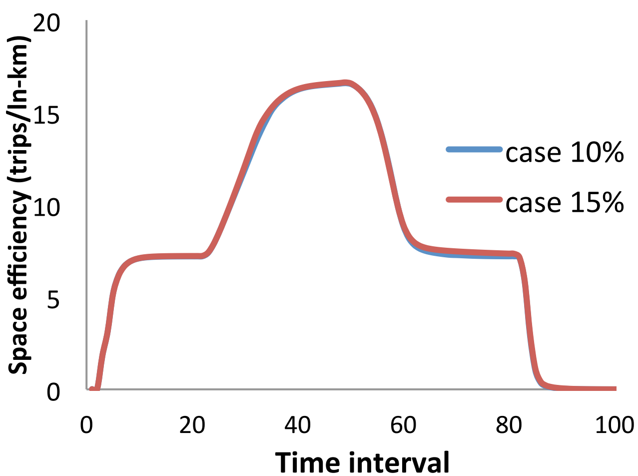
- Mixed traffic in periphery
- Dedicated bus lanes in center

Results - Optimal *static* space distribution

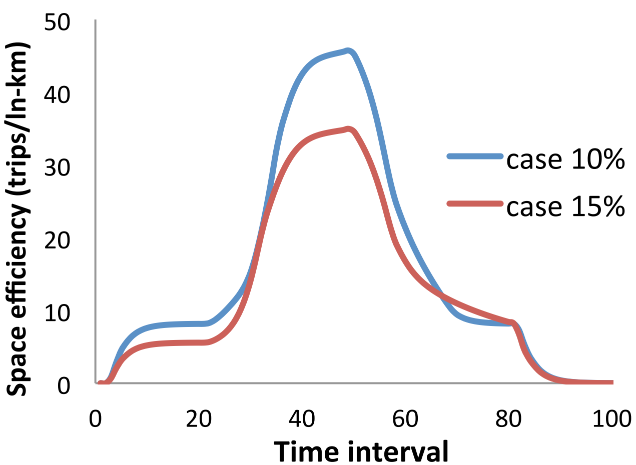




Space efficiency for all modes (trips/ln-km):



Space efficiency for bus lanes (trips/ln-km):



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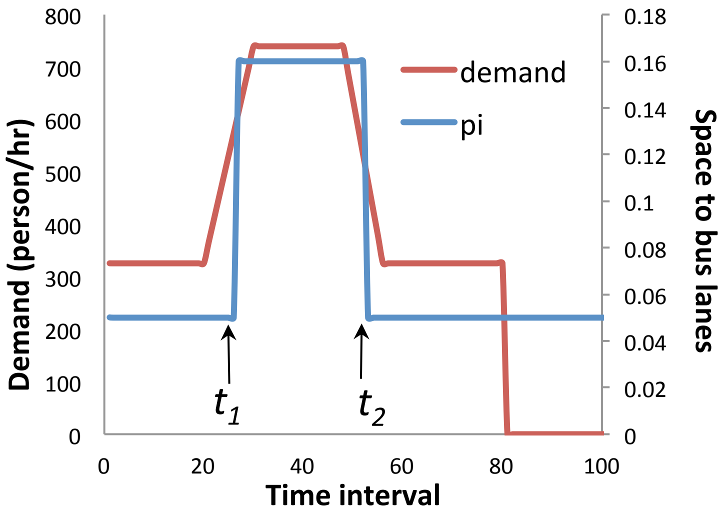
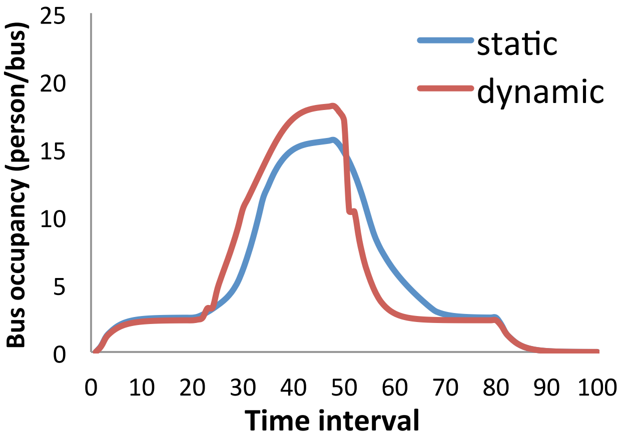
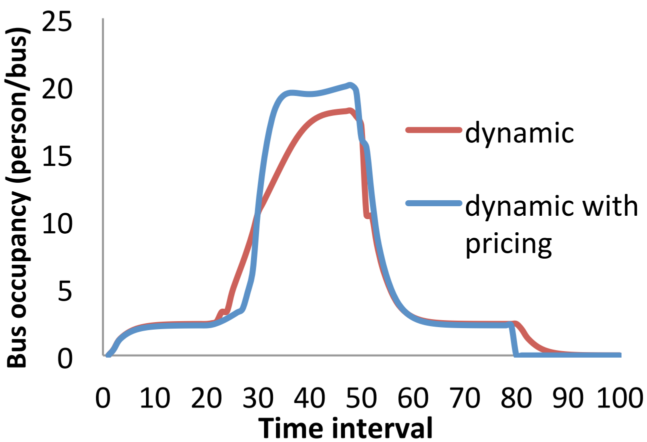
FÉDÉRALE DE LAUSANNE

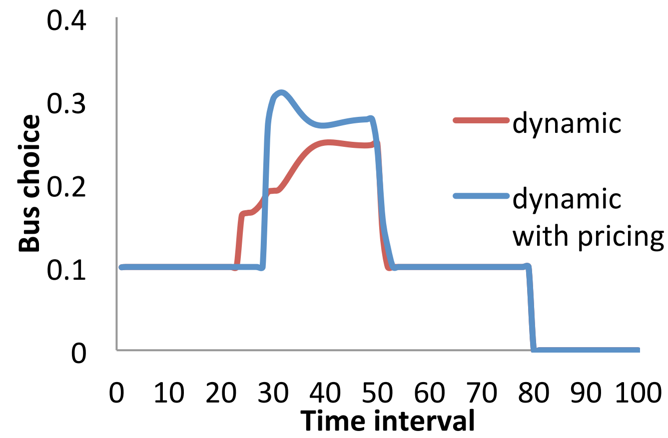
Results - Optimal *dynamic* space distribution

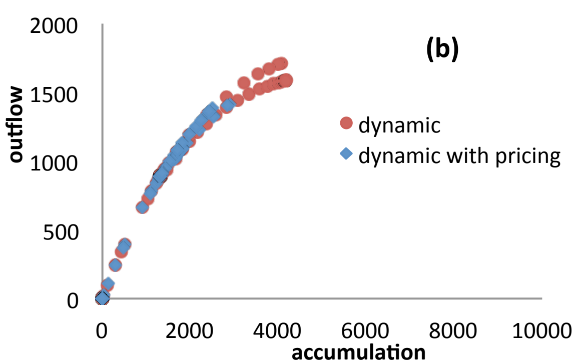




Results - Optimal *dynamic* space distribution *& pricing*

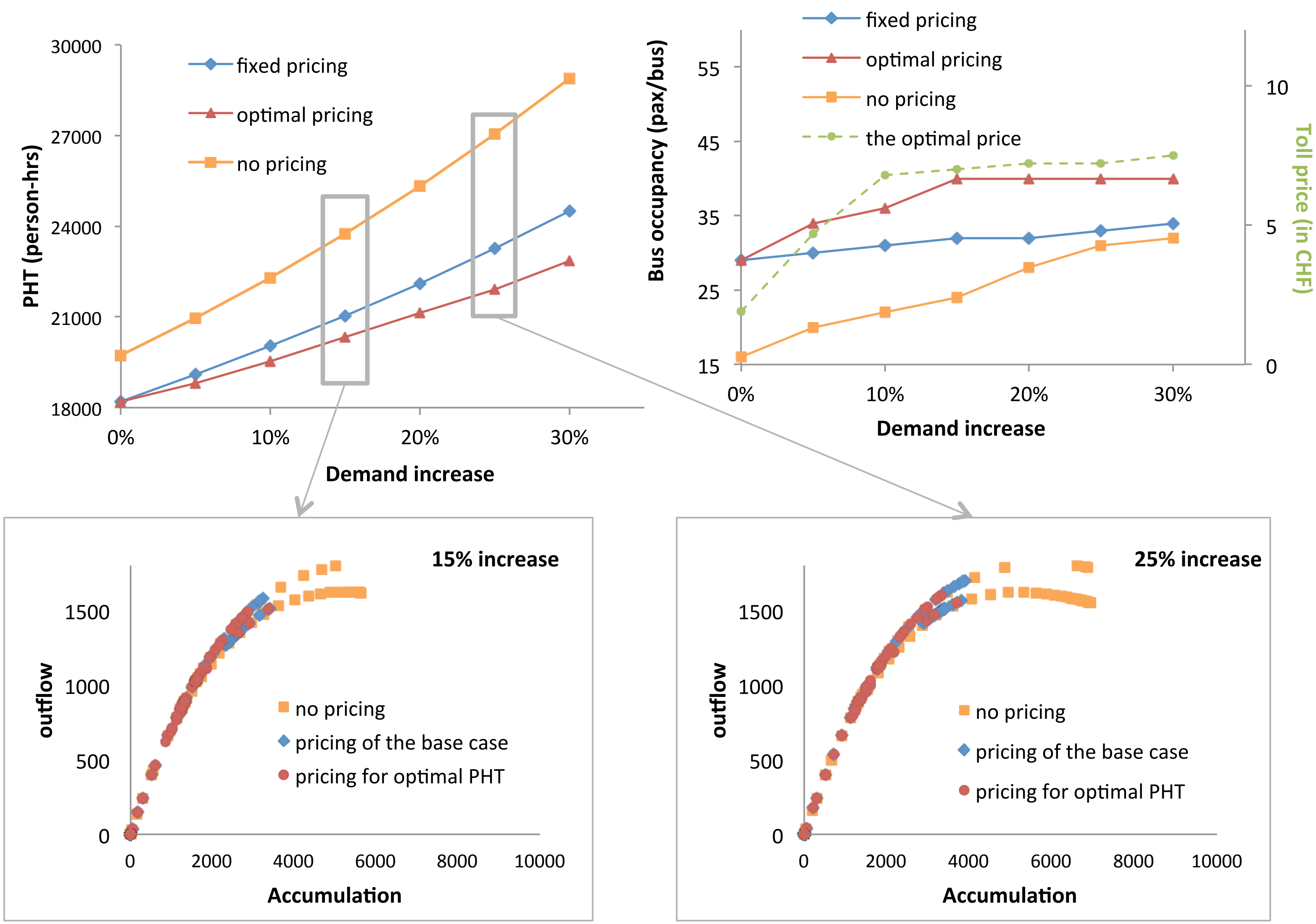






- More reliable MFD states
- TOLL = DELAY SAVINGS
- Robust in demand uncertainty
- Robust in Demand increase

Results – Demand Increase



Ongoing work

- Deeper analysis of multiple regions
- Incorporating cruising-for-parking + restriction/pricing
- Combining space distribution with signal control, bus priority
- Intergrating additional modes
- Validation with field-data
- Heterogeneity among users and different regions