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Traffic Flow in Urban Networks: Models, Simulations, and Control

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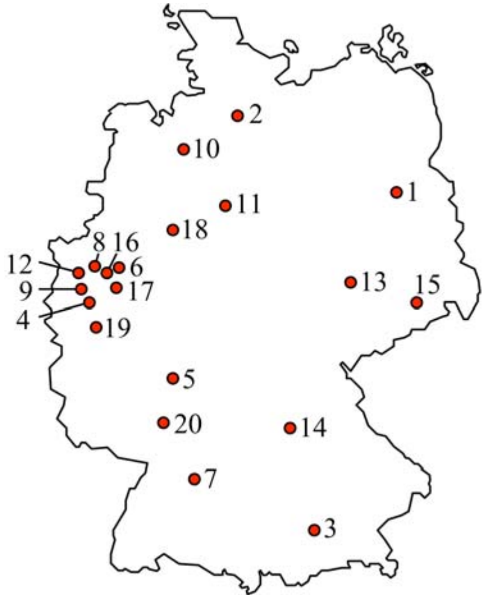
Scaling Laws in the Spatial Structure of Urban Road Networks

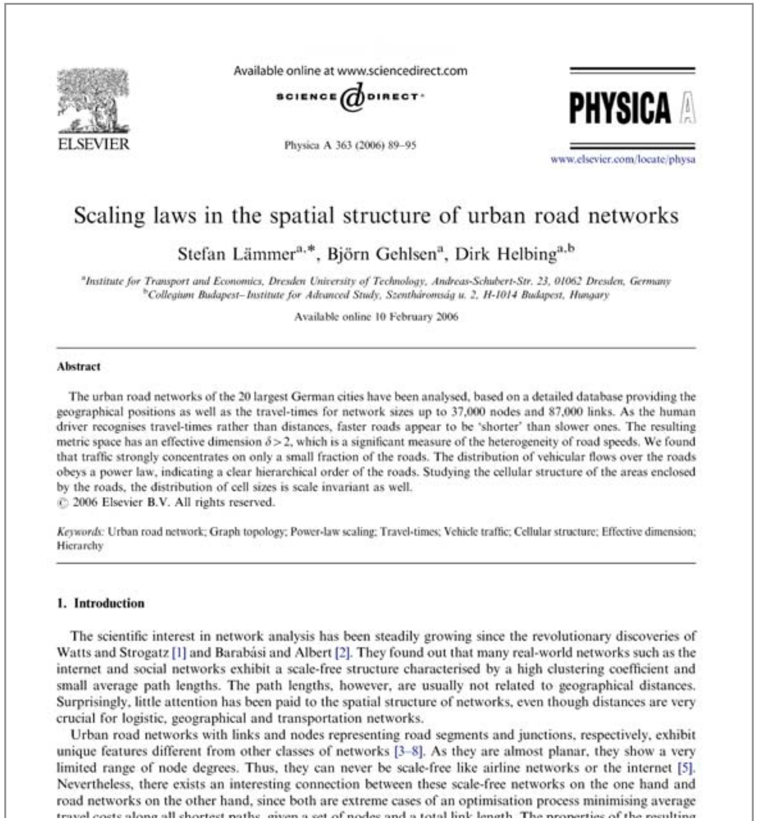
Data Set and Publication

- Urban road network analysis of 20 largest cities of Germany (ranked by population)
- Geographical database: Tele Atlas MultiNet™



Tele Atlas

City of Dresden with 9643 nodes and 22.307 links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Scaling laws in the spatial structure of urban road networks

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Abstract

The urban road networks of the 20 largest German cities have been analysed, based on a detailed database providing the geographical positions as well as the travel-times for network sizes up to 37,000 nodes and 87,000 links. As the human driver recognises travel-times rather than distances, faster roads appear to be 'shorter' than slower ones. The resulting metric space has an effective dimension $\delta > 2$, which is a significant measure of the heterogeneity of road speeds. We found that traffic strongly concentrates on only a small fraction of the roads. The distribution of vehicular flows over the roads obeys a power law, indicating a clear hierarchical order of the roads. Studying the cellular structure of the areas enclosed by the roads, the distribution of cell sizes is scale invariant as well.

Keywords: Urban road network; Graph topology; Power-law scaling; Travel-times; Vehicle traffic; Cellular structure; Effective dimension; Hierarchy

1. Introduction

The scientific interest in network analysis has been steadily growing since the revolutionary discoveries of Watts and Strogatz [1] and Barabási and Albert [2]. They found out that many real-world networks such as the internet and social networks exhibit a scale-free structure characterised by a high clustering coefficient and small average path lengths. The path lengths, however, are usually not related to geographical distances. Surprisingly, little attention has been paid to the spatial structure of networks, even though distances are very crucial for logistic, geographical and transportation networks.

Urban road networks with links and nodes representing road segments and junctions, respectively, exhibit unique features different from other classes of networks [3–8]. As they are almost planar, they show a very limited range of node degrees. Thus, they can never be scale-free like airline networks or the internet [5]. Nevertheless, there exists an interesting connection between these scale-free networks on the one hand and road networks on the other hand, since both are extreme cases of an optimisation process minimising average

Acknowledgements

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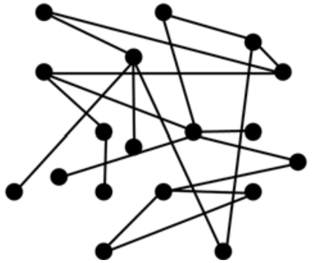
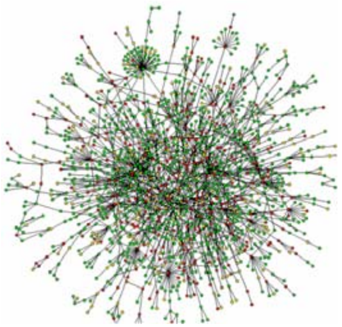
Distinct Classes of Networks

- Random networks *(Erdős and Rényi 1959)*
  - Exponential node-degree distribution
  - High vulnerability to random failures
- Scale-free networks *(Barabasi and Albert 1999)*
  - Short distances (small world phenomenon)
  - High clustering coefficients
  - Power-law node-degree distribution
- Urban road networks *(Gastner and Newman 2004)*
  - Mainly planar cellular structure
  - Limited node-degrees (average strictly less than 6)
  - Very high network diameter, high redundancy





We found scaling laws in
1. the sizes of neighbourhoods
2. the spatial distribution of traffic
3. the cellular structure

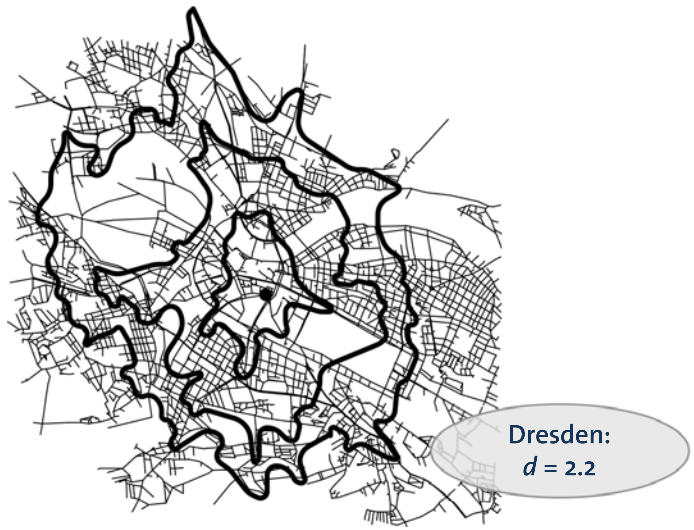
Scaling of Neighborhood Sizes

With a travel-**distance**-budget of ***r* kilometers**, a car driver can reach a neighborhood of size

$$N(r) \sim r^2$$

With a travel-**time**-budget of ***τ* minutes**, a car driver can reach a neighborhood of size

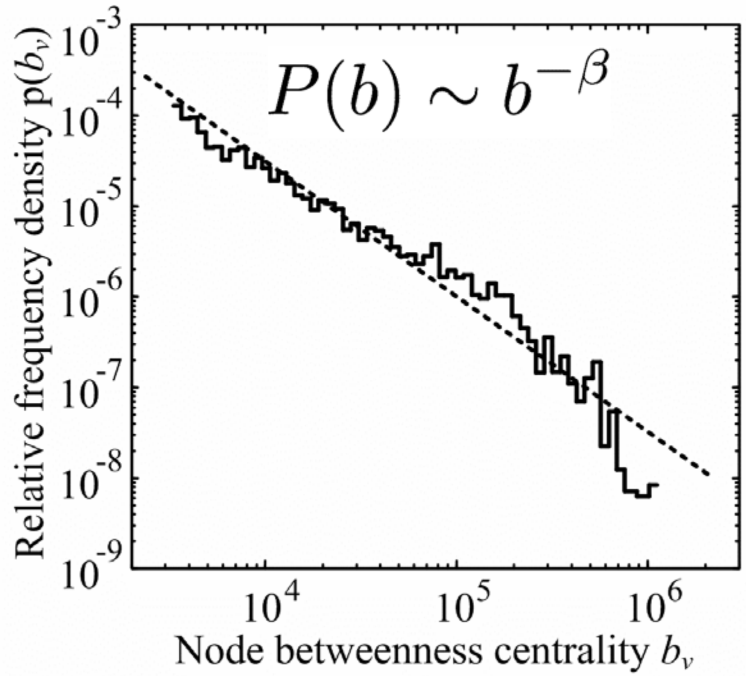
$$N(\tau) \sim \tau^d$$



Spatial Concentration of Traffic Flow

Traffic flows can be characterized by the **betweenness centrality *b***, which is the number of shortest paths visiting a link or a node. (We assume homogeneous OD-flows and ignore congestion effects.)

Scaling of Traffic Flow on Nodes

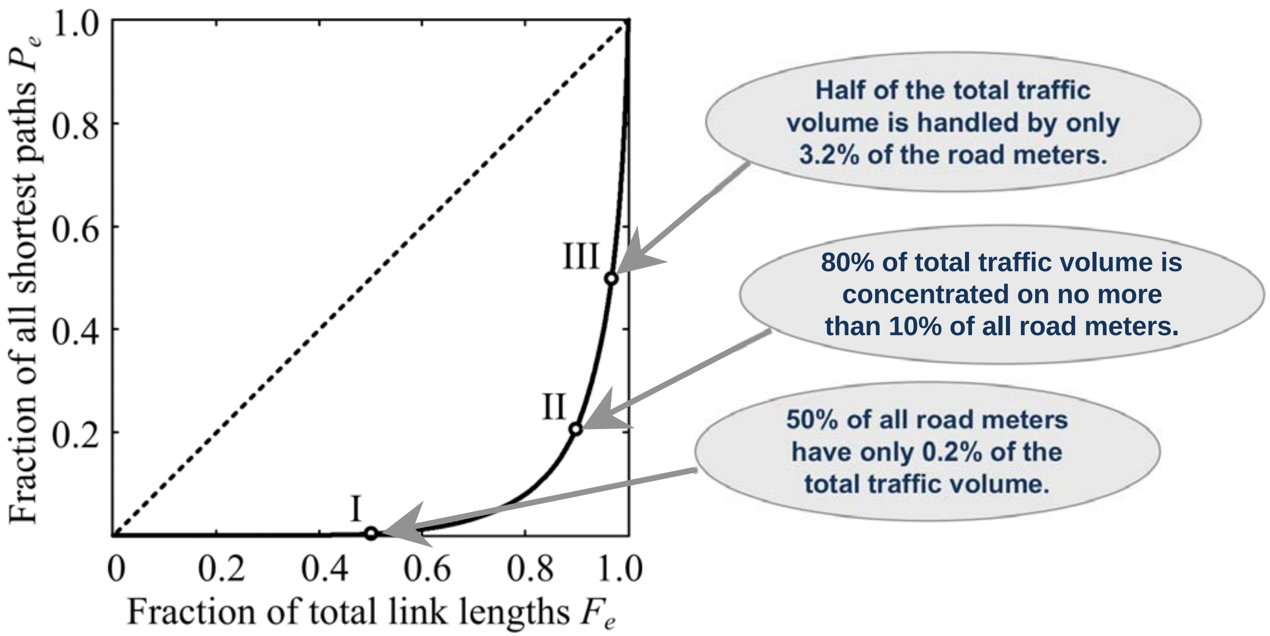


Typical values for β	
Berlin	1.481
Hamburg	1.469
Munich	1.486
Cologne	1.384
Frankfurt	1.406
Dortmund	1.340
Stuttgart	1.377
Essen	1.368
Düsseldorf	1.380
Bremen	1.351
Duisburg	1.480
Leipzig	1.320
Nuremberg	1.420
Dresden	1.355
Bochum	1.337
Wuppertal	1.279
Bielefeld	1.337
Bonn	1.374

- High values of $\boldsymbol{\beta}$ imply:
  - Traffic flow concentrates on few highly important intersections.
  - Low redundancy (lack of alternative routes)
  - High vulnerability to failures of traffic control

Concentration of Traffic on Road Meters

- Lorenz-Curve



- High values of Gini-Coefficient ***g*** imply
  - Bundling of traffic on arterial roads
  - Existence of bottlenecks (bridges)
  - Reduced traffic (in residential areas)
  - Distinct hierarchy of roads

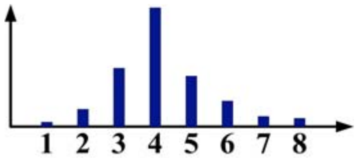
Typical values for g

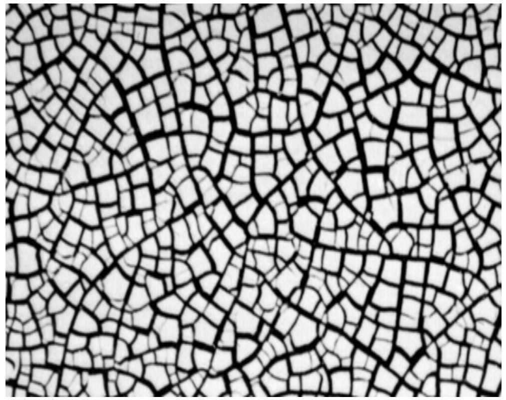
Berlin	0,871	Stuttgart	0,894	Nuremberg	0,854
Hamburg	0,869	Essen	0,892	Dresden	0,870
Munich	0,869	Düsseldorf	0,849	Bochum	0,847
Cologne	0,875	Bremen	0,909	Wuppertal	0,881
Frankfurt	0,873	Duisburg	0,900	Bielefeld	0,872
Dortmund	0,875	Leipzig	0,880	Bonn	0,889

Cellular Structures

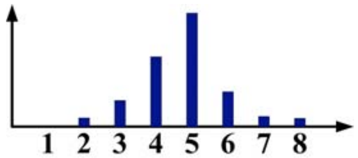
Distribution of cell-degrees (number of neighboring cells)

Road networks

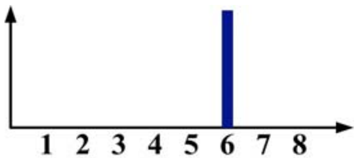


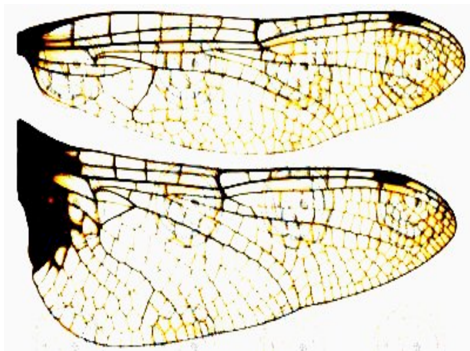


Crack patterns

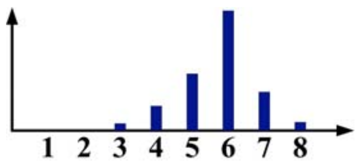


Honey combs

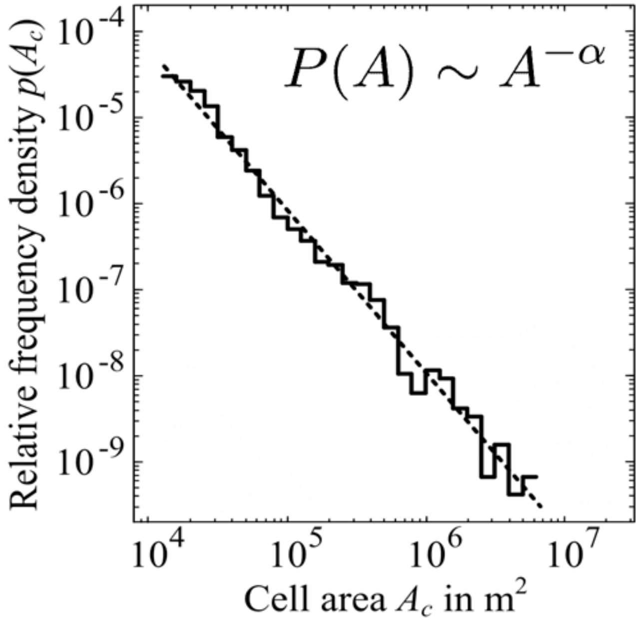


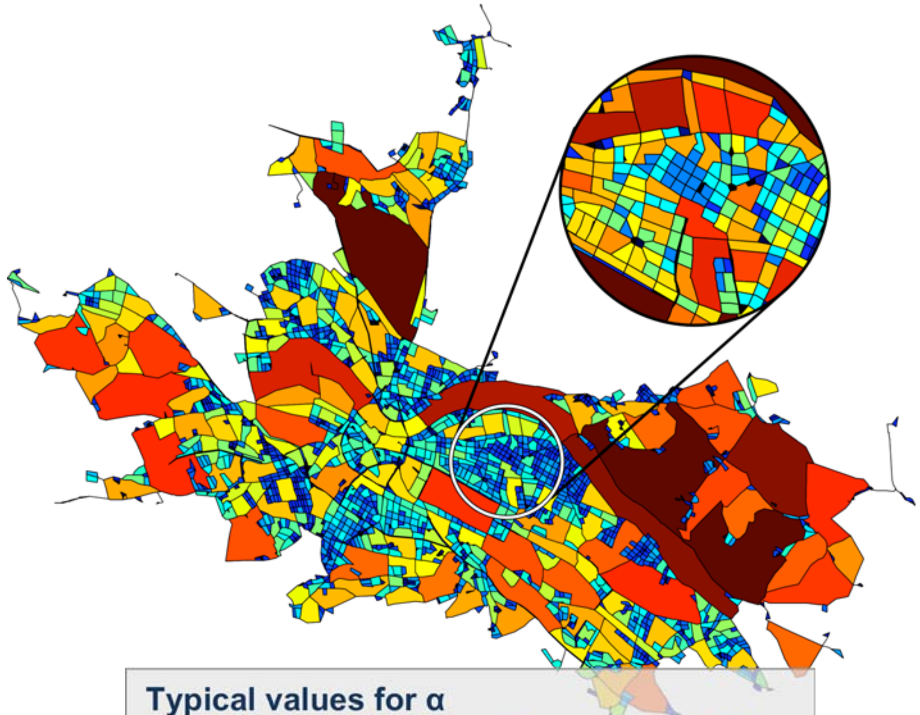


Dragon fly wings



Scaling of Cell Areas





$$\frac{P(A/2)}{P(A)} = 2^{\alpha} \approx 4$$

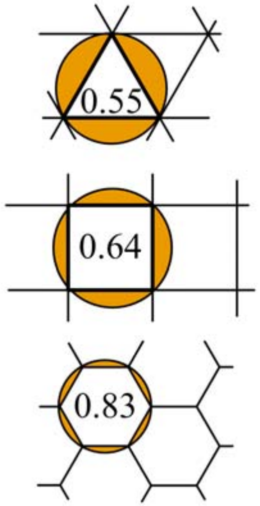
Cells with half the cell area are four times more frequent

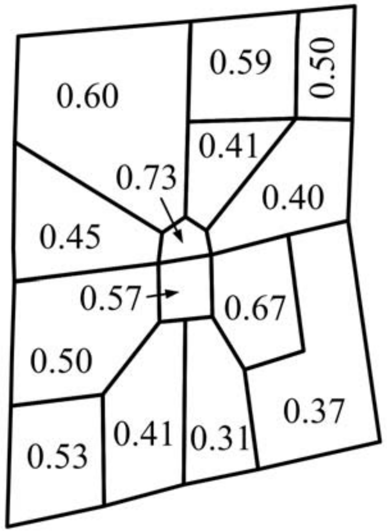
Typical values for α

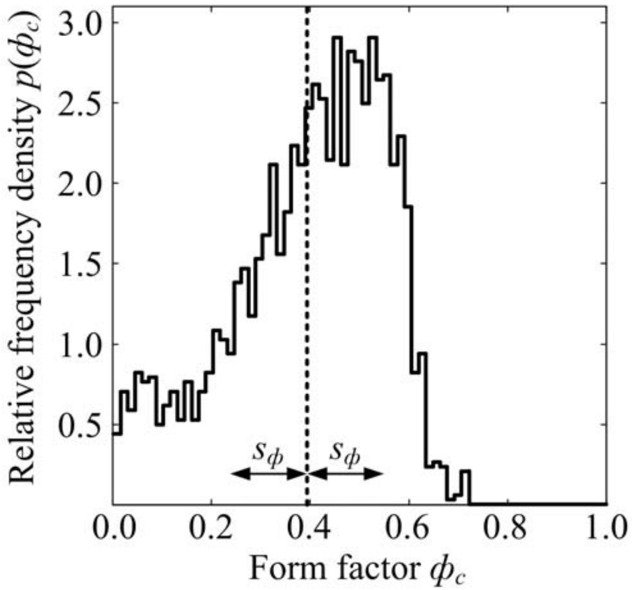
Berlin	2.158	Bremen	1.931
Hamburg	1.890	Duisburg	1.924
Munich	2.114	Leipzig	1.926
Cologne	1.922	Nuremberg	1.831
Frankfurt	2.009	Dresden	1.892
Dortmund	1.803	Bochum	1.829
Stuttgart	1.901	Wuppertal	1.883
Essen	1.932	Bielefeld	1.735
Düsseldorf	1.964	Bonn	2.018

Distribution of Form Factors

- Form factor φ: Fraction of the circumscribed circle that is covered by the cell
  φ=0 ... long and narrow
  φ=1 ... compact and round





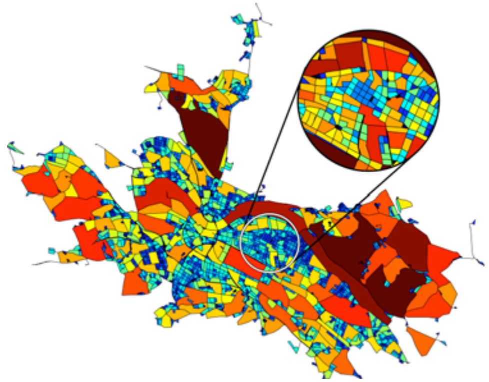


	Var(φ)
Berlin	0,159
Hamburg	0,164
Munich	0,159
Cologne	0,165
Frankfurt	0,169
Dortmund	0,166
Stuttgart	0,170
Essen	0,169
Düsseldorf	0,175
Bremen	0,166
Duisburg	0,169
Leipzig	0,153
Nuremberg	0,172
Dresden	0,156
Bochum	0,171
Wuppertal	0,162
Bielefeld	0,161
Bonn	0,173

- High values of **Var(φ)** imply
  - Irregular network structure,
    e.g. city has grown over many epochs
  - Difficult to navigate from car driver's point of view

Intermediate Conclusions

- Scaling of neighborhood sizes
  - Fast roads let neighborhoods grow fast
  - Effective dimension of urban space is significantly higher than two (although mainly planar)
- Scaling of traffic flow
  - Estimation of traffic based on betweenness centrality
  - Power-law distribution of traffic flow on nodes
  - We found quantitative measures to characterize concentration of traffic
- Scaling of cell areas
  - Power-law distribution of cell areas
  - We found quantitative measures to characterize irregularity of cellular structure



Implementation of an Decentralized and Self-Organized Traffic Light Control

Optimal Traffic Flow Control and Production Scheduling

- Traffic is a prime example of a complex system consisting of interacting queues

- Optimization algorithms can be transferred to production systems, sometimes organizations

- Vehicles correspond to products, traffic lights to service stations or machines

- Formulas for travel times relate to formulas for cycle times (production times)

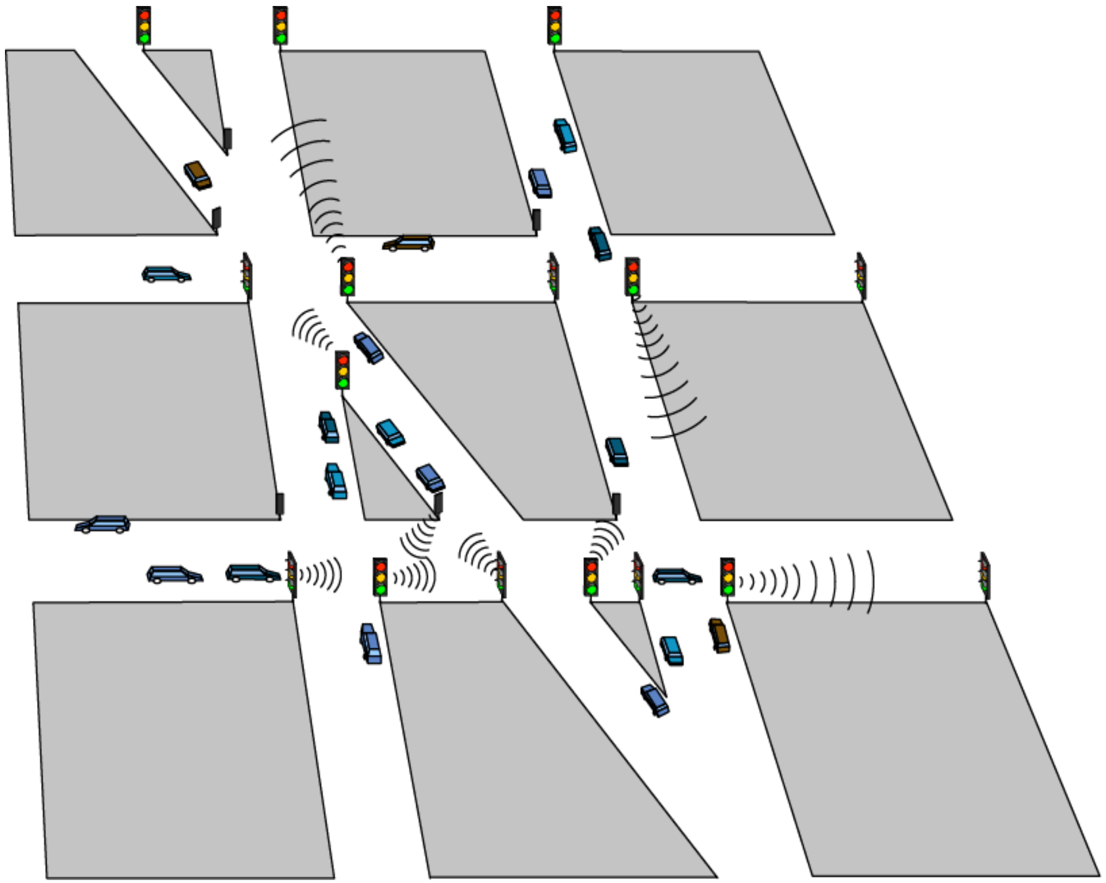
- Conflicts in usage (e.g. of intersection areas) require priority rules and scheduling strategies which are adaptive to a varying demand.

Analogies to Production Networks

Road Networks		Production Networks
Directed Links:		
▪ Road sections	⇔	Buffers
▪ Travel- and delay time	⇔	Cycle time
▪ Congestion, queues	⇔	Full buffers
Nodes:		
▪ Junctions	⇔	Processing units
▪ Different origin-destination	⇔	Different products flows
▪ Conflicting flows	⇔	Conflicts in usage of gripper, transfer cars etc.
▪ Traffic light scheduling	⇔	Production scheduling
▪ Green Wave	⇔	ConWiP strategy
▪ Accidents	⇔	Machine breakdowns

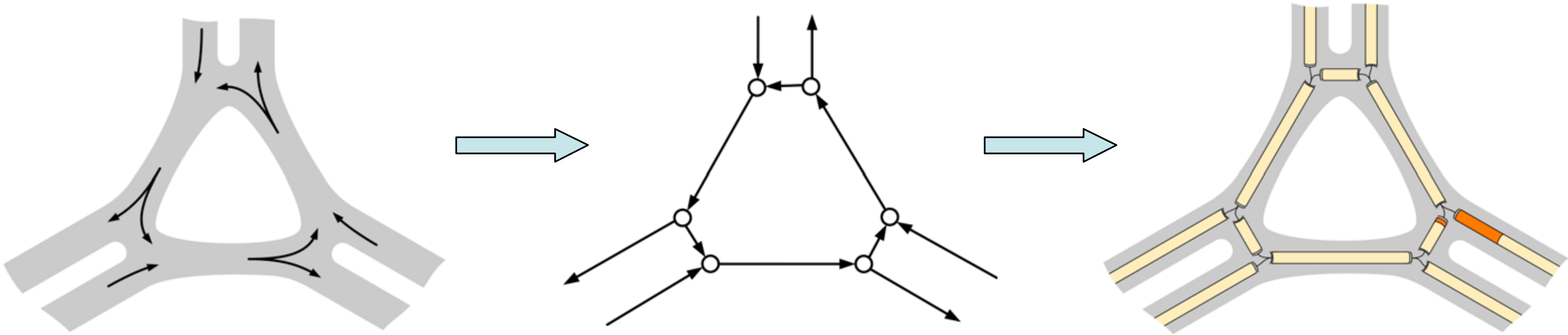
Adaptive Traffic Light Control

- for complex street networks
- for traffic disruptions (building sites, accidents, etc.)
- for particular events (Olympic games, pop concerts, etc.)



Road Network as Directed Graph

- **Directed links** are homogenous road sections
  - Traffic dynamics: congestion, queues
- **Nodes** are connectors between road sections
  - Junctions: merging, diverging



- **Intersections**
  - Traffic lights: control, optimization
- **Traffic assignment**
  - Route choice, destination flows

**Local Rules,
Decentralization,
Self organization**

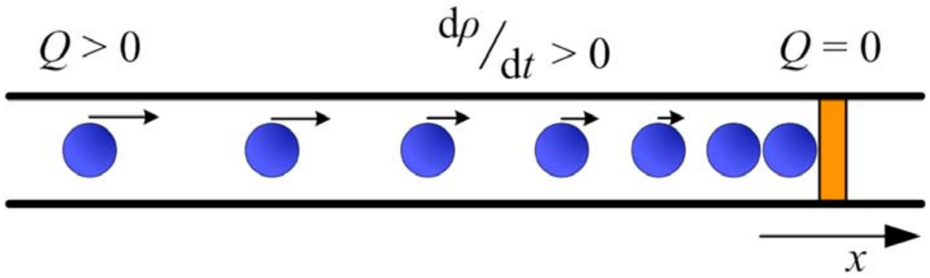
Traffic Dynamics: Macroscopic Approach

- "Traffic is a fluid medium."
  - Describing values:

$$\begin{array}{lll} V & \ldots & \text{velocity (in m/s)} \\ \rho & \ldots & \text{density (in vcl/m)} \\ Q & \ldots & \text{flow (in vcl/s)} \end{array}$$

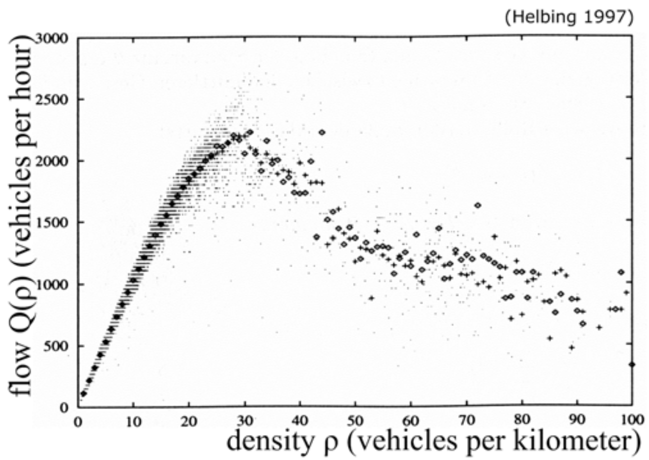
- Conservation of vehicles
  - Continuity equation:

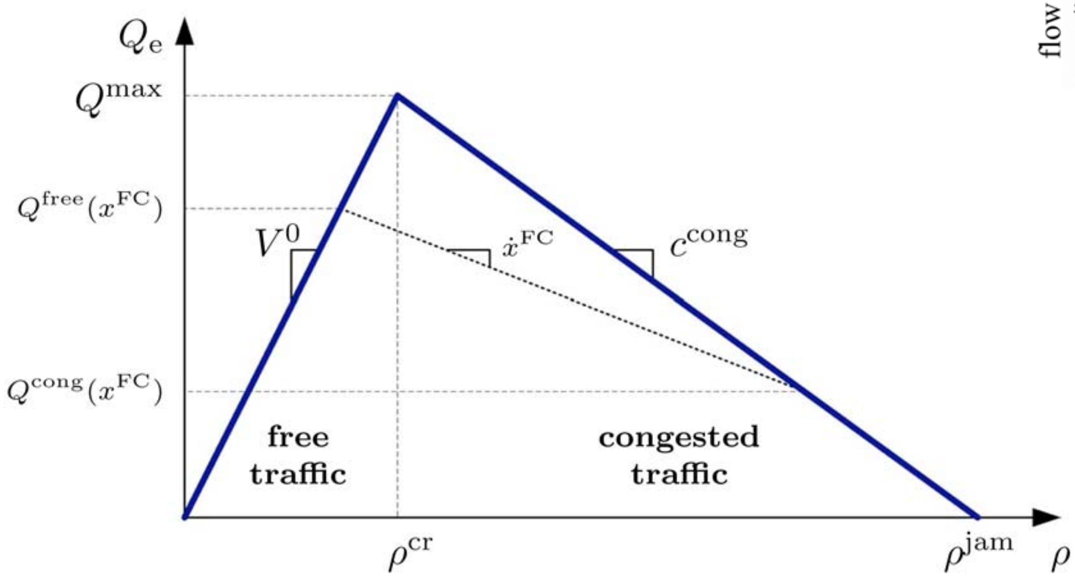
$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial Q(x,t)}{\partial x} = 0$$



Traffic Dynamics: Fundamental Diagram

- "Flow Q and density ρ are empirically correlated."





$$\frac{\partial \rho}{\partial t} + \underbrace{\frac{dQ_e(\rho)}{d\rho}}_{c(\rho)} \cdot \frac{\partial \rho}{\partial x} = 0$$

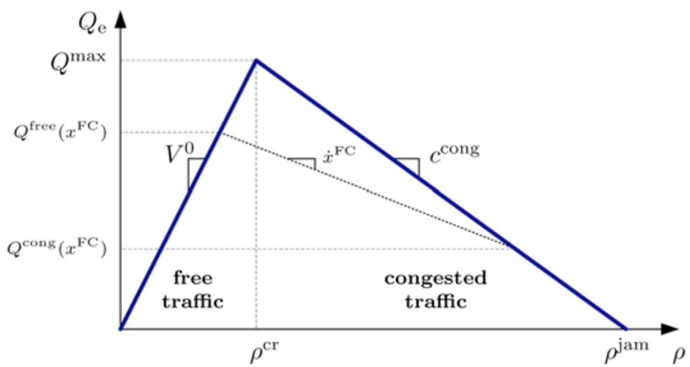
Derivation Q_e' plays important role!

Traffic Dynamics: Shock Waves

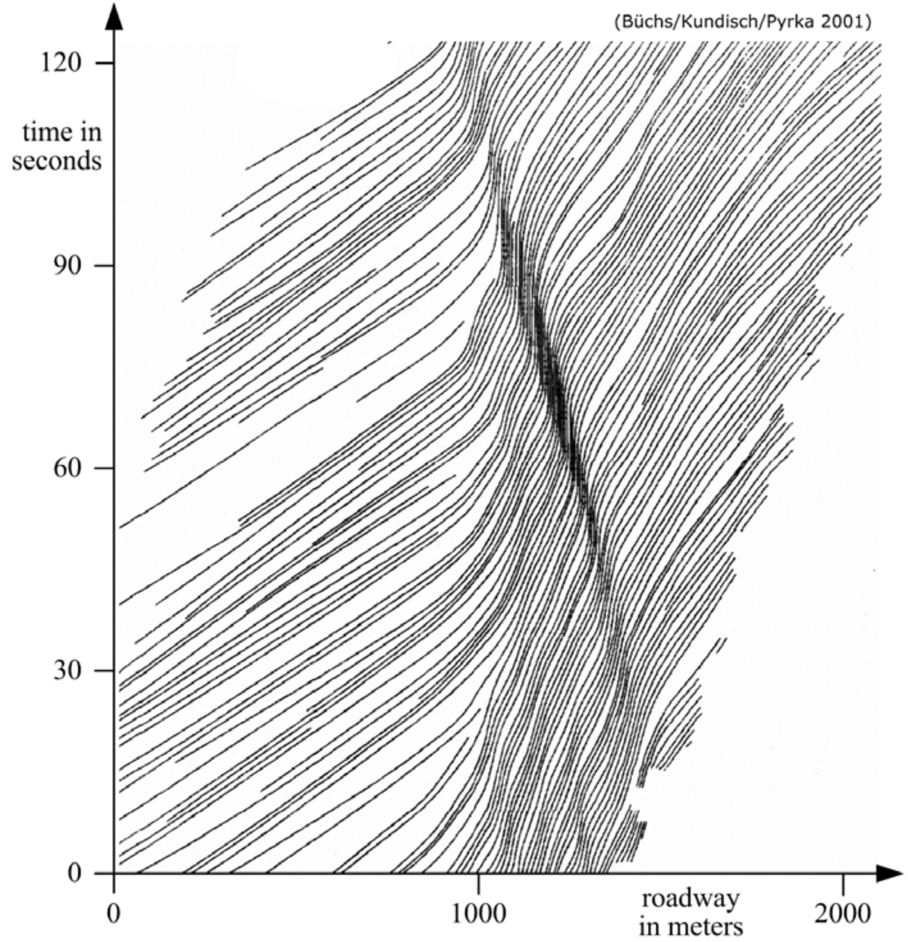
- Propagation velocity $c(\rho)$

$$c(\rho) = \frac{\mathrm{d}Q_\mathrm{e}(\rho)}{\mathrm{d}\rho}$$

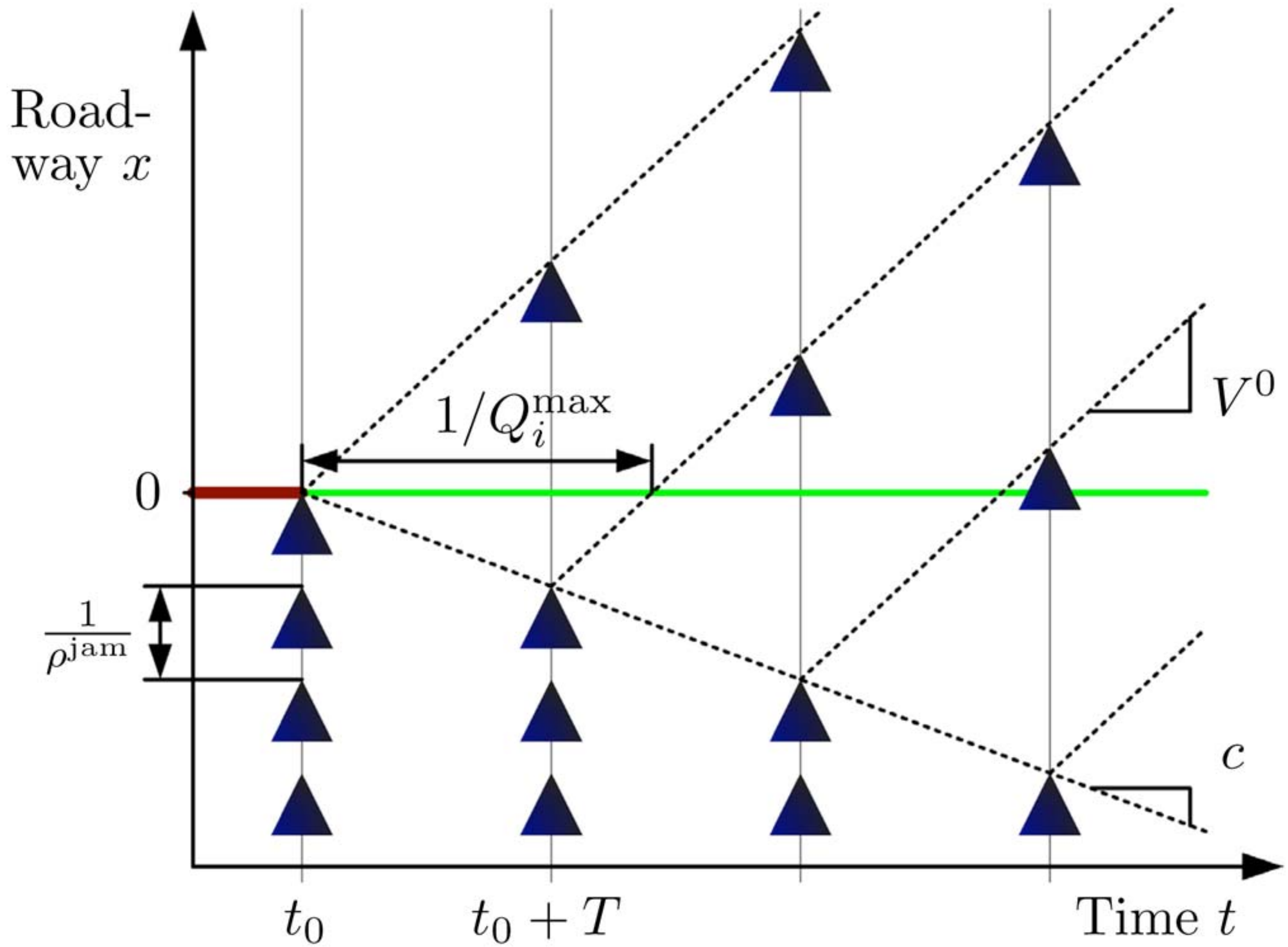
- Free traffic:
  - $c(\rho) = V^0$
- Congested traffic:
  - $c(\rho) \approx$ -15 km/h (universal)



(Büchs/Kundisch/Pyrka 2001)



Characteristic Velocities



A Queueing-Theoretical Traffic Model

The continuity equation for the vehicle density $\rho(x,t)$ at place x and time t in road section i is

$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial Q_i(x,t)}{\partial x} = \text{Source Terms}$$

We assume the fundamental flow-density relation

$$Q_i(\rho) = \begin{cases} Q_i^{\text{free}}(\rho) = \rho V_i^0 & \text{if } \rho < \rho_{\text{cr}} \\ Q_i^{\text{cong}}(\rho) = (1 - \rho / \rho_{\text{jam}}) / T & \text{otherwise} \end{cases}$$

V_i^0 = free speed on road section i

T = safe time gap

ρ_{jam} = jam density

The number N_i of vehicles in section i changes according to

$$\frac{dN_i(t)}{dt} = Q_i^{\text{arr}}(t) - Q_i^{\text{dep}}(t) = Q_{i-1}^{\text{dep}}(t) + Q_{i-1}^{\text{ramp}}(t) - Q_i^{\text{dep}}(t)$$

Q_i^{arr} = arrival rate of vehicles

Q_i^{dep} = departure rate of vehicles

Treatment of ramp flows at downstream section ends:

$$Q_{i+1}^{\text{arr}}(t) = Q_i^{\text{dep}}(t) + Q_i^{\text{ramp}}(t)$$

A Queueing-Theoretical Traffic Model

The traffic-state dependent departure rate is given by

$$Q_i^{\text{dep}}(t) = \begin{cases} Q_i^{\text{arr}}(t - T_i^{\text{free}}) & \text{if } S_{i+1}(t) \neq 1 \text{ and } S_i(t) = 0 \\ Q_i^{\text{cap}}(t) & \text{if } S_{i+1}(t) \neq 1 \text{ and } S_i(t) \neq 0 \\ Q_i^{\text{dep}}(t - T_{i+1}^{\text{cong}}) - Q_i^{\text{ramp}}(t) & \text{if } S_{i+1}(t) = 1 \end{cases}$$

The capacity of congested road section is:

$$Q_i^{\text{cap}}(t) = I_i Q_{\text{out}}(t) - \max[Q_i^{\text{ramp}}(t), (I_i - I_{i+1})Q_{\text{out}}, \Delta Q_i(t), 0]$$

I_i = number of lanes

$Q_{\text{out}} = (1 - \rho_{\text{cr}}/\rho_{\text{jam}})/T$ = outflow per lane from congested traffic

The maximum capacity in free traffic is:

$$Q_i^{\text{max}}(t) = I_i \rho_{\text{cr}} V_i^0 - \max[Q_i^{\text{ramp}}(t), (I_i - I_{i+1})\rho_{\text{cr}} V_i^0, \Delta Q_i(t), 0]$$

Definition of free ($S_i = 0$), fully congested ($S_i = 1$) and partially congested ($S_i = 2$) traffic states:

$$S_i(t) = \begin{cases} 0 & \text{if } l_i(t) = 0 \text{ and } Q_i^{\text{arr}}(t - dt - T_i^{\text{free}}) < Q_i^{\text{max}}(t - dt) \\ 1 & \text{if } l_i(t) = L_i \text{ and } Q_i^{\text{dep}}(t - dt - T_i^{\text{cong}}) \leq Q_i^{\text{arr}}(t - dt) \\ 2 & \text{otherwise} \end{cases}$$

L_i = length of road section i, l_i = length of congested road section

A Queueing-Theoretical Traffic Model

Growth of the length l_i of congested traffic according to shock wave theory:

$$\frac{dl_i}{dt} = -\frac{Q_i^{\text{dep}}(t - l_i(t)/c) - Q_i^{\text{arr}}(t - [L_i - l_i(t)]/V_i^0)}{\rho_i^{\text{cong}}(Q_i^{\text{dep}}(t - l_i(t)/c)/I_i) - \rho_i^{\text{free}}(Q_i^{\text{arr}}(t - [L_i - l_i(t)]/V_i^0)/I_i)}$$

with densities

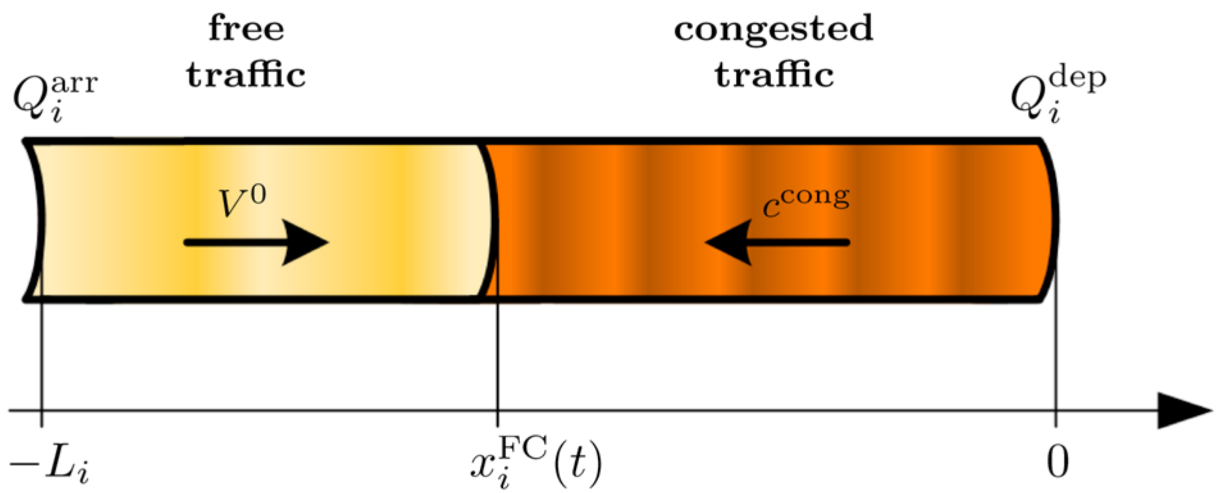
$$\rho_i^{\text{free}}(Q_i) = Q_i / V_i^0,$$

$$\rho_i^{\text{cong}}(Q_i) = (1 - TQ_i)\rho_{\text{jam}}$$

Delay-differential equation for the travel time T_i on section i, when entered at time t:

$$\frac{dT_i(t)}{dt} = \frac{Q_i^{\text{arr}}(t)}{Q_i^{\text{dep}}(t + T_i(t))} - 1 = \frac{Q_{i-1}^{\text{dep}}(t) + Q_{i-1}^{\text{ramp}}(t)}{Q_i^{\text{dep}}(t + T_i(t))} - 1$$

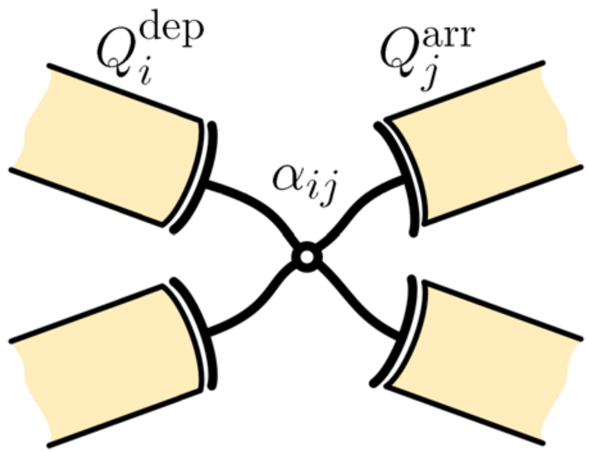
Network Links: Homogenous Road Sections

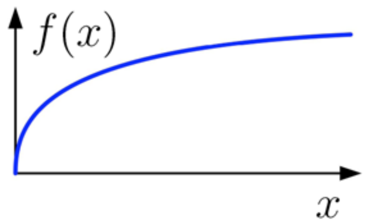


- Movement of congestion $$\frac{\mathrm{d}}{\mathrm{d}t} x_i^{\mathrm{FC}} = \frac{\Delta Q\left(x_i^{\mathrm{FC}}\right)}{\Delta \rho\left(x_i^{\mathrm{FC}}\right)}$$
- Number of vehicles $$\frac{\mathrm{d}}{\mathrm{d}t} N_i(t) = Q_i^{\mathrm{arr}}(t) - Q_i^{\mathrm{dep}}(t)$$
- Travel time $$\frac{\mathrm{d}}{\mathrm{d}t} T_i(t) = 1 - \frac{Q_i^{\mathrm{dep}}(t)}{Q_i^{\mathrm{arr}}(t - T_i(t))}$$

Network Nodes: Connectors

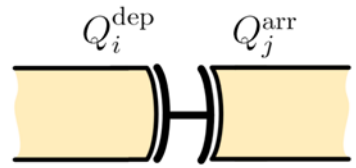
- Side Conditions
  $$\sum_i Q_i^{\text{dep}} = \sum_j Q_j^{\text{arr}}$$
  - Conservation
    $$Q_i^{\text{dep}} \geq 0$$
    $$Q_j^{\text{arr}} \geq 0$$
  - Non-negativity
    $$Q_i^{\text{dep}} \leq Q_i^{\text{dep,pot}}$$
    $$Q_j^{\text{arr}} \leq Q_j^{\text{arr,pot}}$$
  - Upper boundary
    $$\sum_i \alpha_{ij} Q_i^{\text{dep}} = Q_j^{\text{arr}}$$
  - Branching
    $$F = \sum_i f(Q_i^{\text{dep}}) \to \max$$
- Goal function
  $$f(x) = x^p \quad \text{with } p \ll 1$$



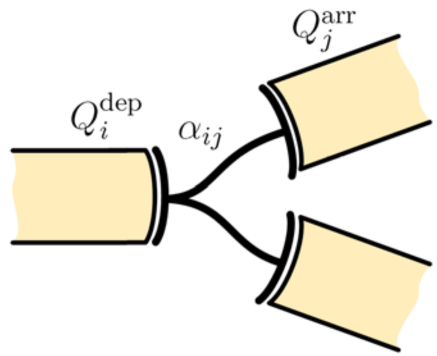


Network Nodes: Special Cases

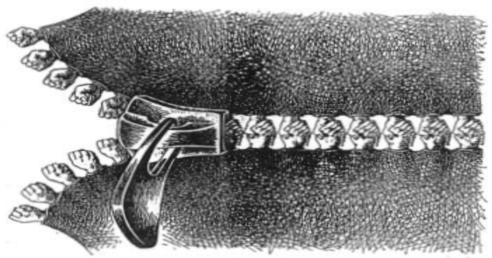
- **1 to 1:** $$Q_i^{\text{dep}} = Q_j^{\text{arr}} = \min\left\{Q_i^{\text{dep,pot}}, Q_j^{\text{arr,pot}}\right\}$$

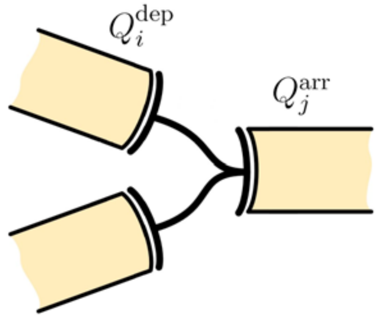


- **1 to n:** Diverging $$Q_i^{\text{dep}} = \min\left\{Q_i^{\text{dep,pot}}, \min_j \frac{Q_j^{\text{arr,pot}}}{\alpha_{ij}}\right\}$$ $$Q_j^{\text{arr}} = \alpha_{ij} Q_i^{\text{dep}}$$

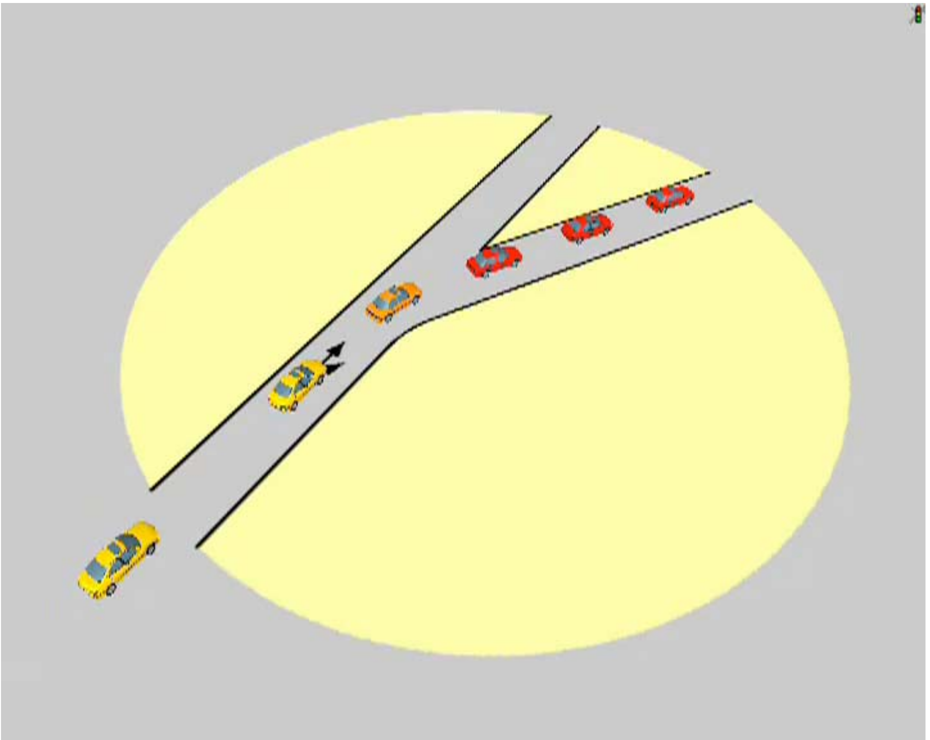


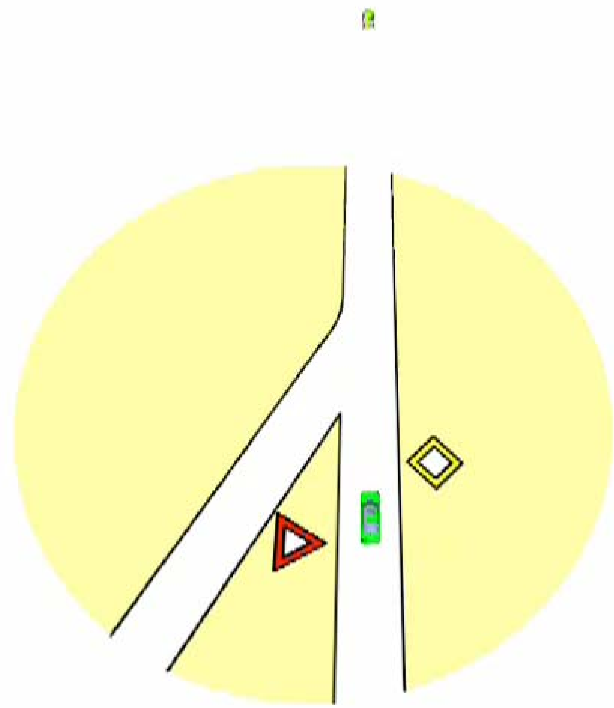
- **n to 1:** Merging





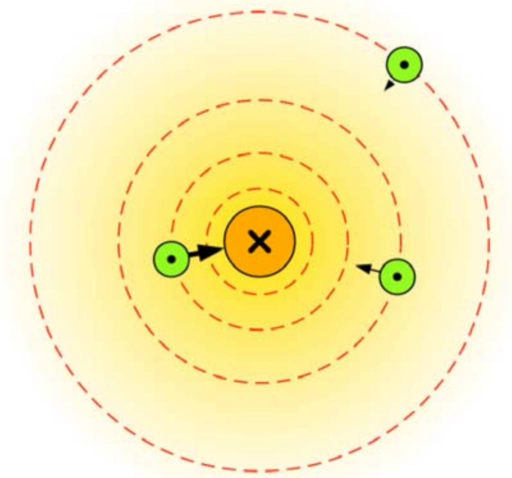
Simulation of Diverges and Merges



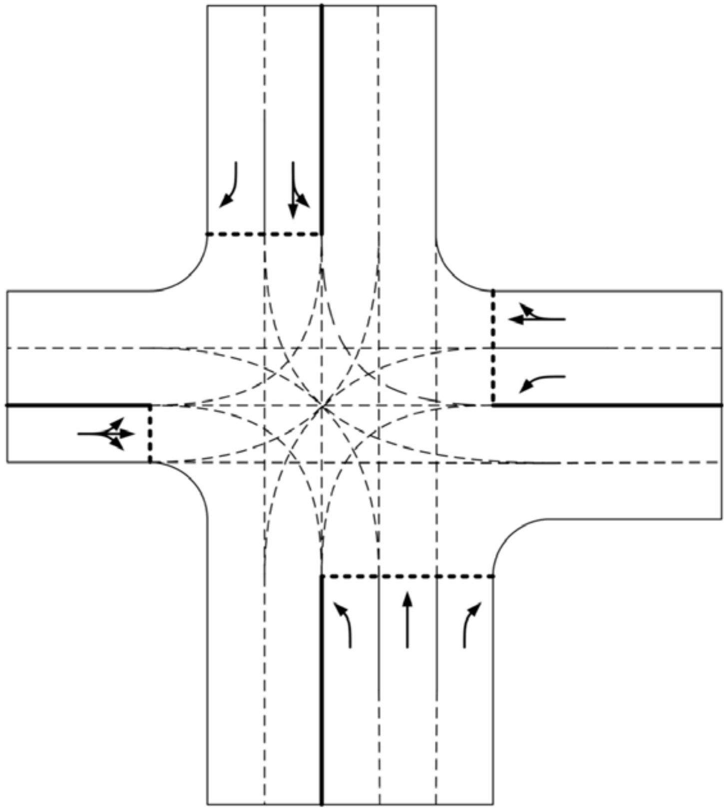


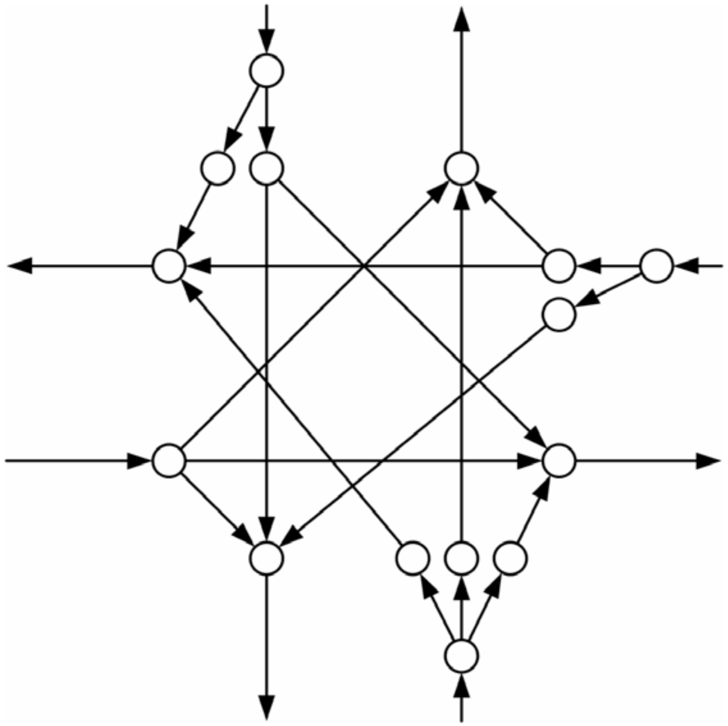
Attractiveness of Sinks

Mathematically, sinks tend
to attract their vehicles similar
to electric charges in a wire

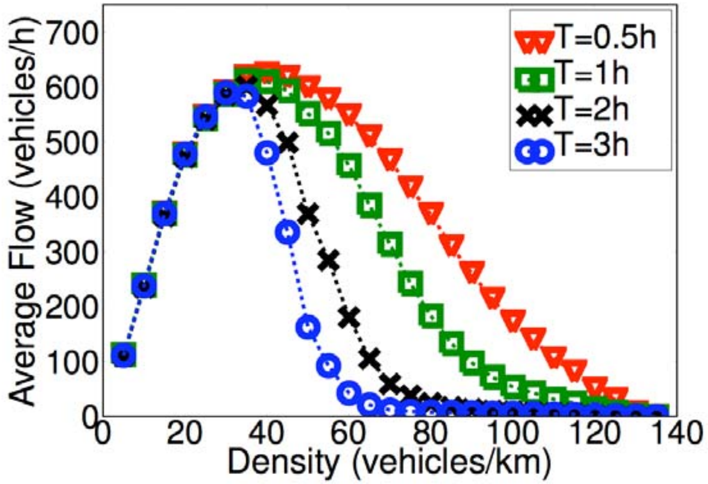


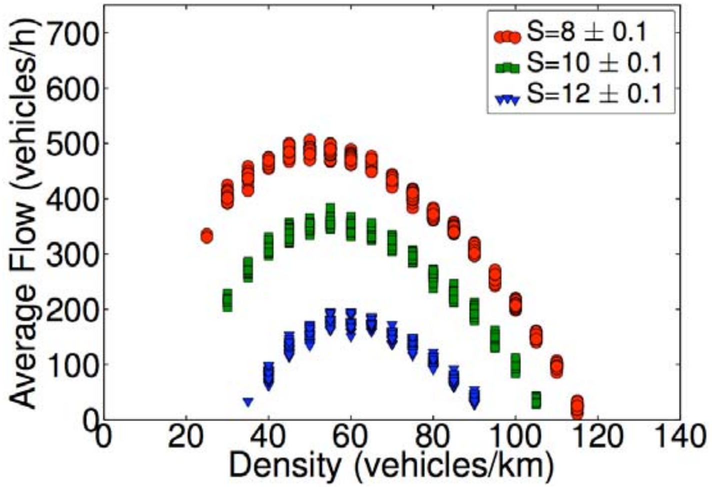
Network Representation of Intersections

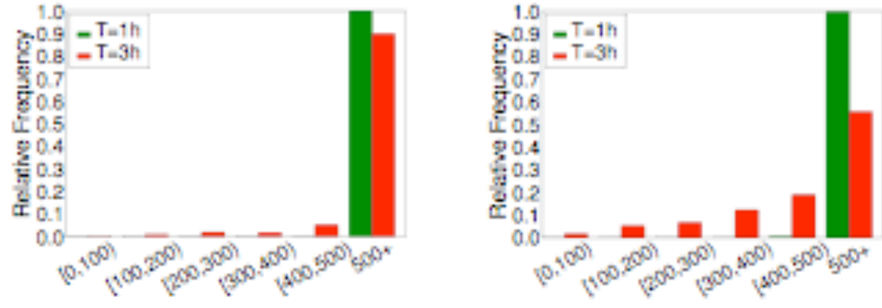




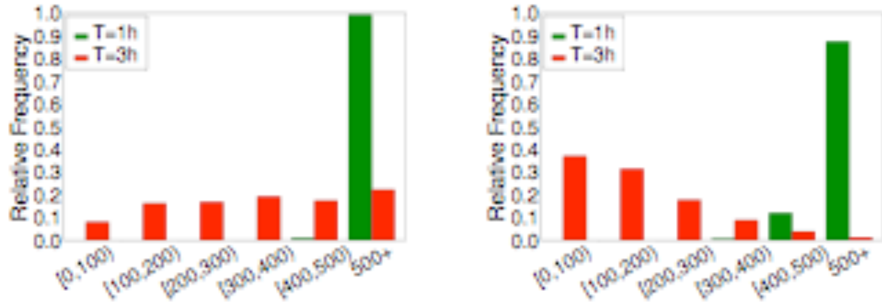
Variability of Urban Traffic Flows

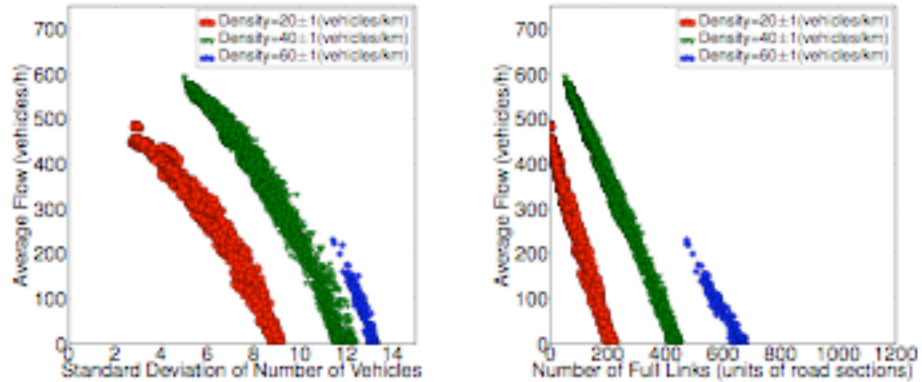






(a) Density=35 vehicles/km (b) Density=40 vehicles/km

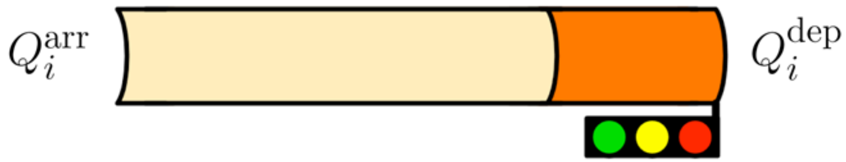




(a) (b)

Intersections: Modelling

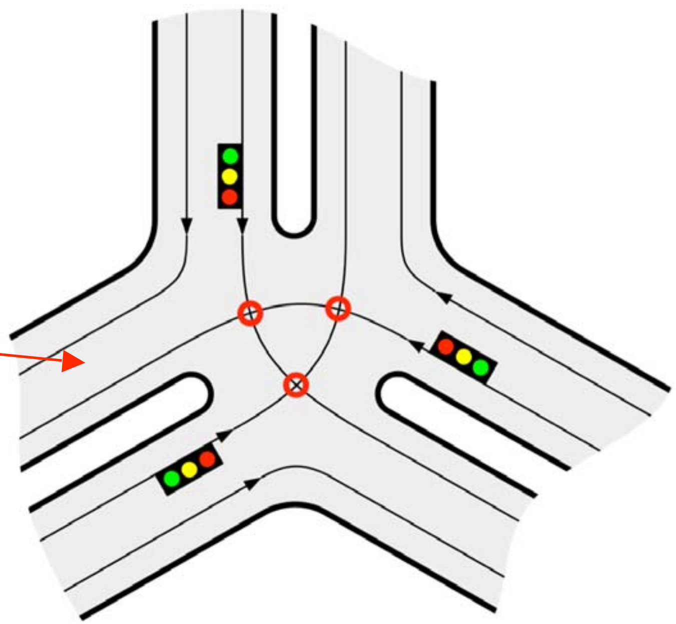
- Traffic light
  - Additional side condition



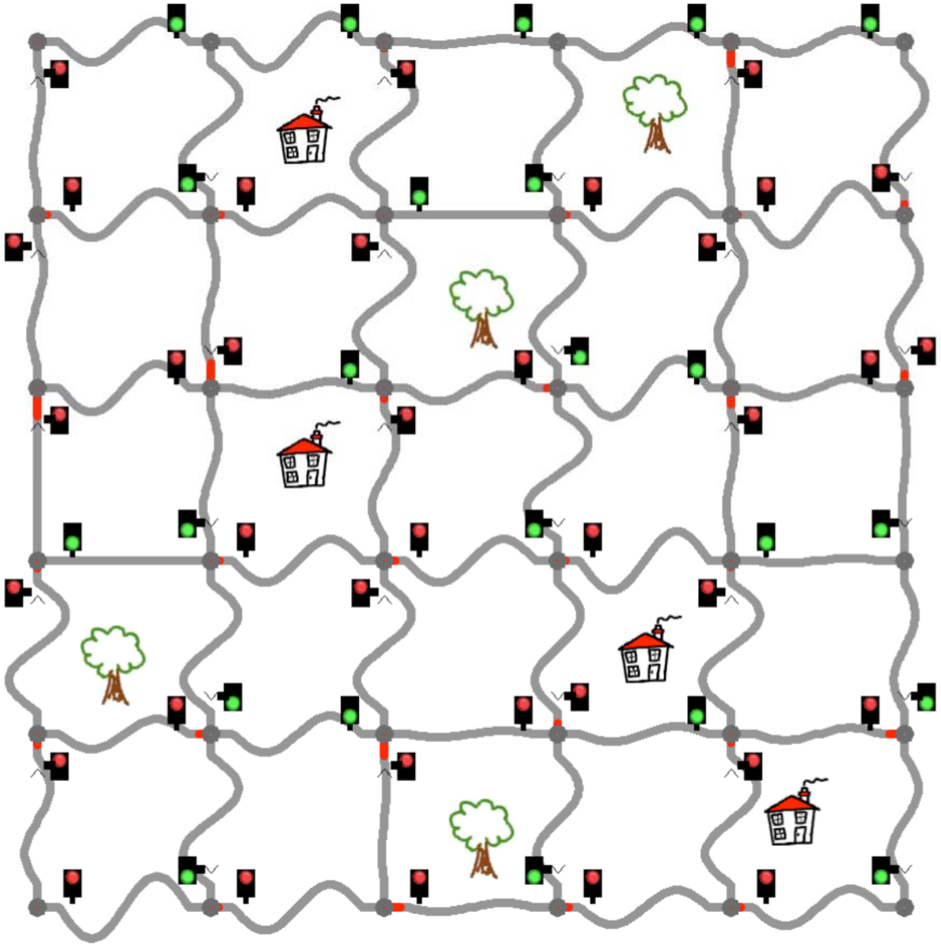
$$Q_i^{\text{dep}}(t) \;\leq\; g(t) \cdot Q_i^{\max}$$

$$0 \leq g(t) \leq 1$$

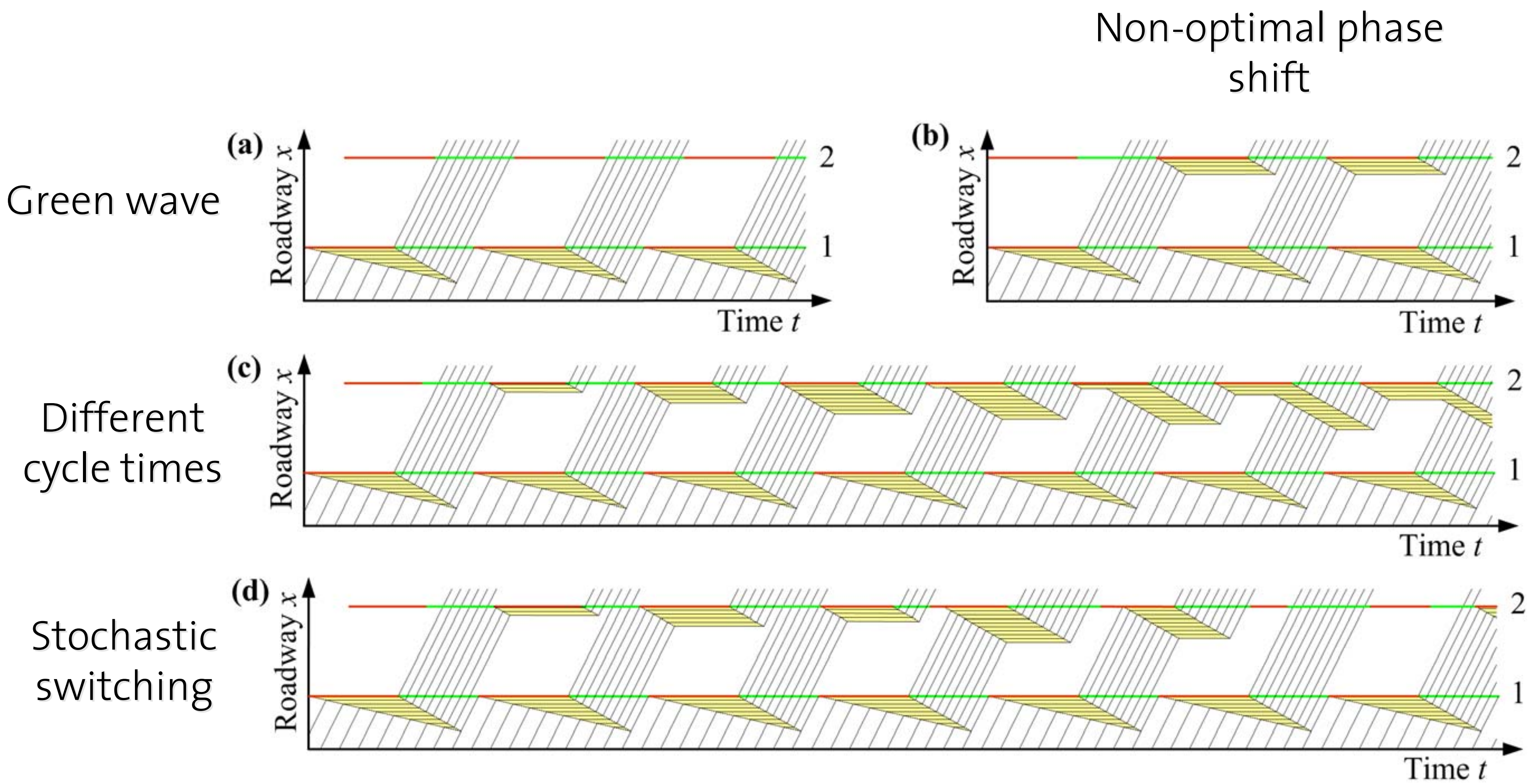
- Intersection
  - Is **only** defined by a set of mutually excluding traffic lights
  - Each intersection point gives one more side condition



Simulation of Artificial Road Networks with Traffic Lights



Interdependence of Subsequent Intersections



Self-Organized Traffic Light Control

Particular Challenges and Difficulties:

- Large variations in demand, turning rates, etc.
- Irregular networks, nodes with 5, 6, 7 links
- Switching times discourage frequent switches, reduce flexibility a lot!
- Queue front does not stay at service station (traffic light, intersection), instead propagates upstream and complicates queue dynamics
- Travel times are dependent on load/congestion level
- Delay times propagate in opposite directions
- Variety of service/turning directions is costly: reduces the fraction of green time for each direction
- Congested subsequent roads can diminish the effect of green times
- Minimum flow property reduces throughput of shared lanes
- Optimal sequence of signal phases changes, optimal solutions are aperiodic!
- Some directions may be served several times, while others are only served one time (i.e. it can make sense to split jobs!)

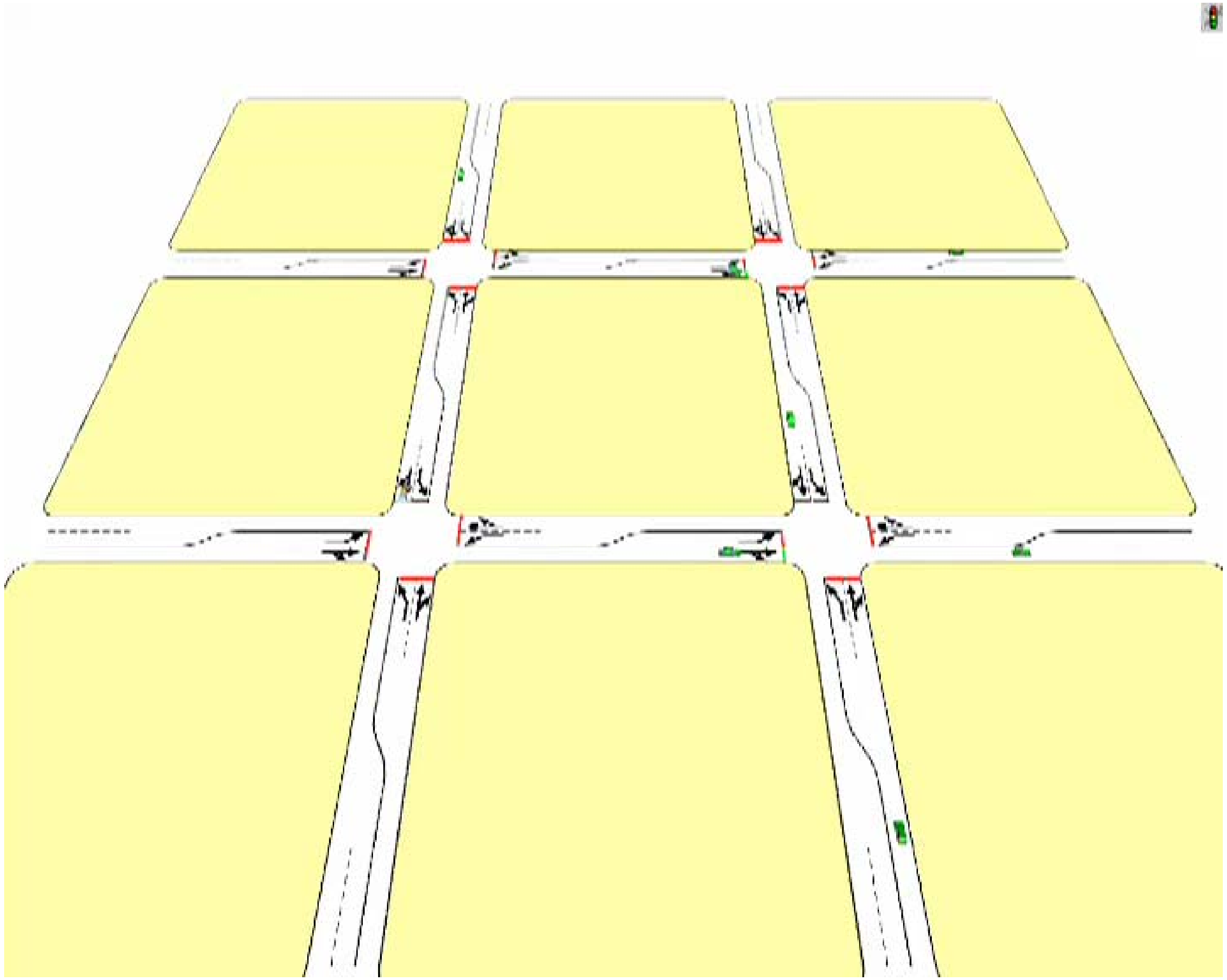
Optimization problem is dominated by non-linearities and NP hard!

Operation Regimes of Traffic Light Scheduling

I. “Gaseous” Free-Flow Low-Density Regime

- Demand considerably below capacity
- Application of the first-in-first-out/first-come-first-serve principle
- Individual cars get green lights upon arrival at intersection
- Default state is a red light!
- All turning directions can be served
- Low throughput because of small vehicle arrival rate

Service of Single Vehicles upon Arrival

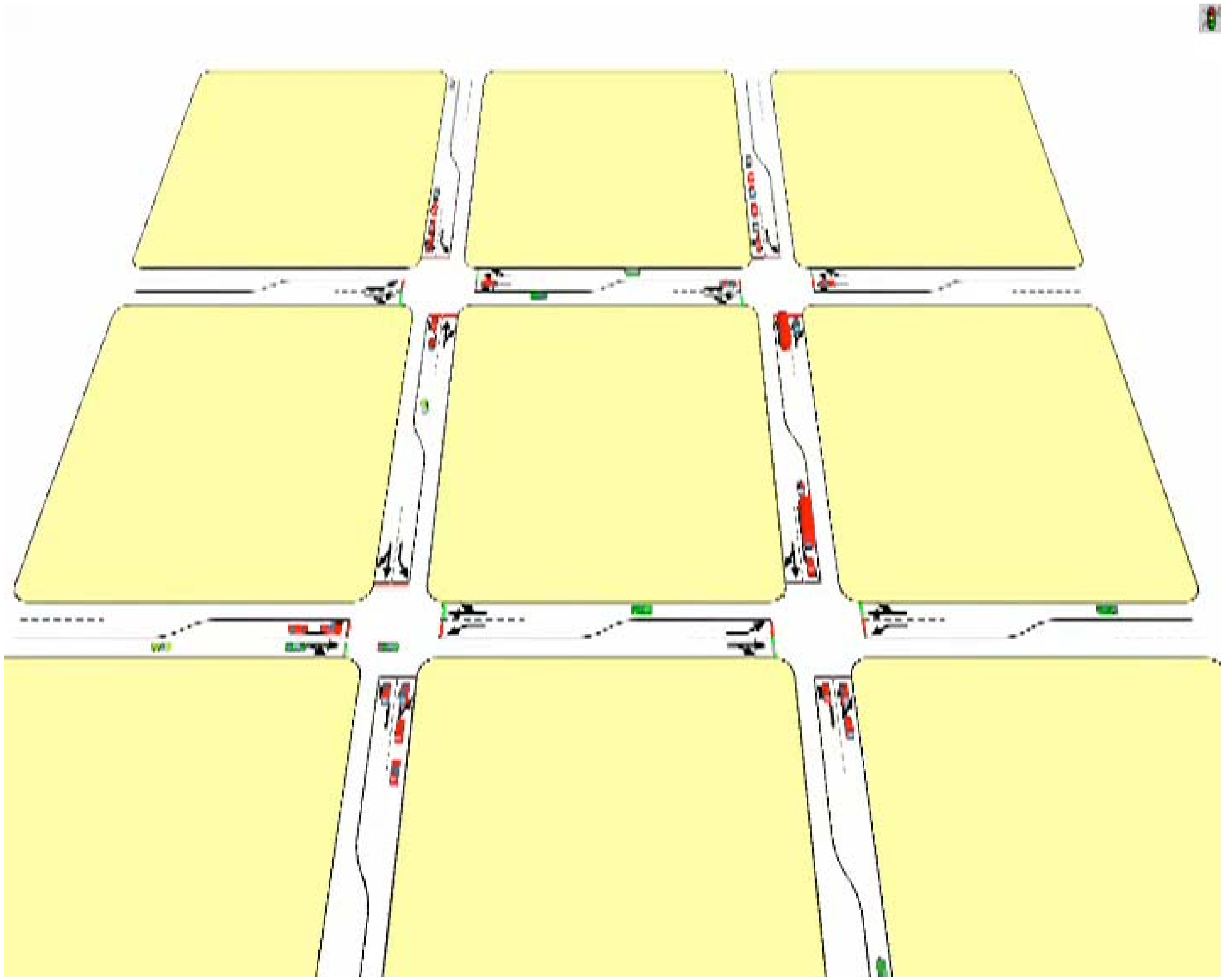


Operation Regimes of Traffic Light Scheduling

II. Droplet-/Platoon-Forming, Mutually Obstructed Regime

- Demand below and possibly close to capacity
- Simultaneous arrivals and, therefore, conflicts of usage likely
- Waiting times are unavoidable. Hence, vehicle platoons are forming
- The goal is to minimize waiting times
- Serving platoons rather than single vehicles increases throughput!
- Longer standing platoons are prioritized compared to shorter ones
- Moving platoons are prioritized compared to similarly long standing platoons. This is essential for traffic light synchronization and formation of green waves.

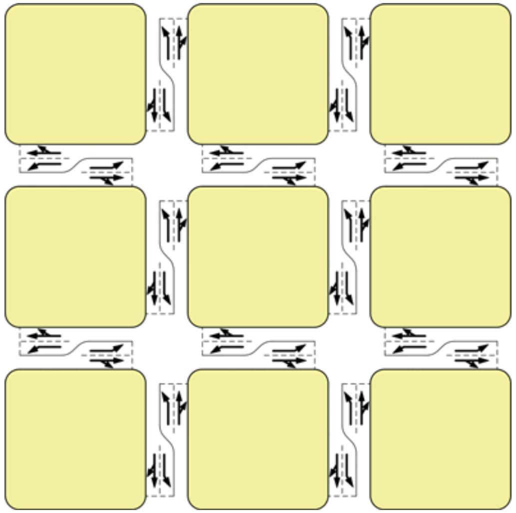
Emergence of Green Waves

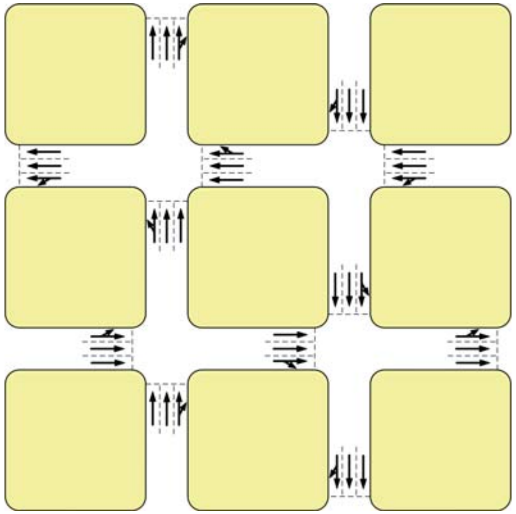


Operation Regimes of Traffic Light Scheduling

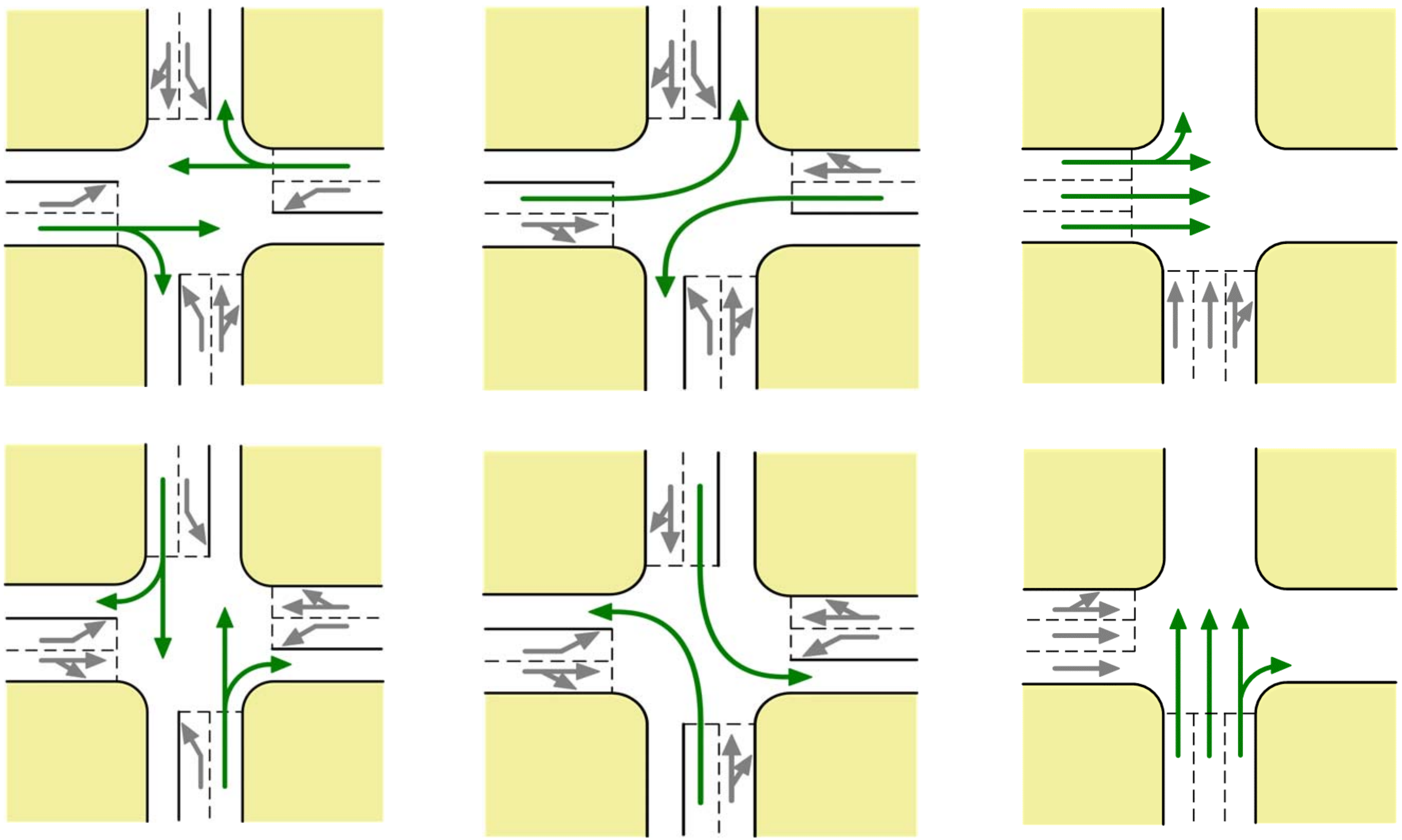
III. Condensed, Congested, Queue-Dominated Regime

- Demand above capacity
- Goal becomes flow maximization, as queues form in all directions
- Application of flow bundling principle (similarly to platoon formation) is recommended: Reduction of service/turning directions, i.e. of heterogeneity, increases capacity

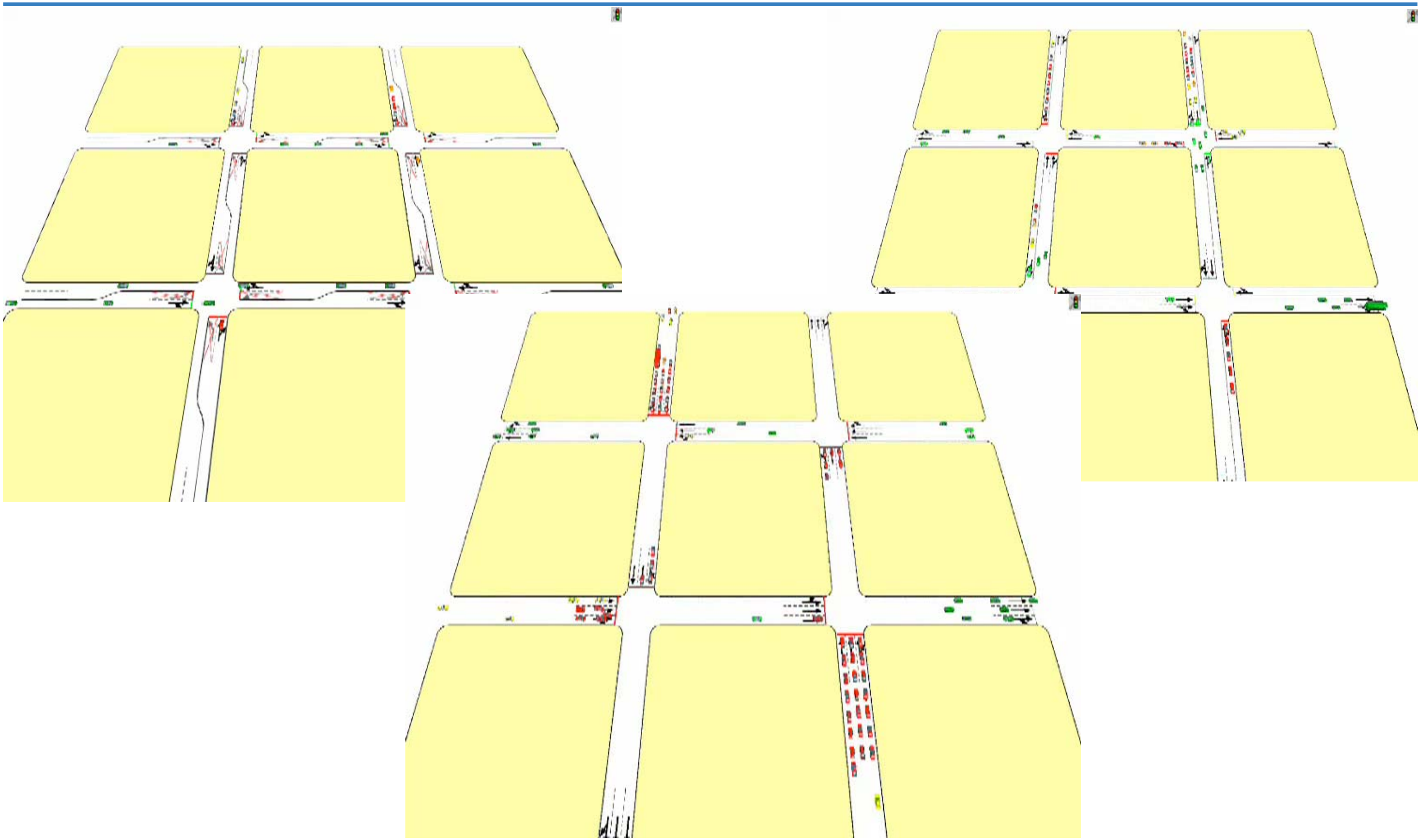


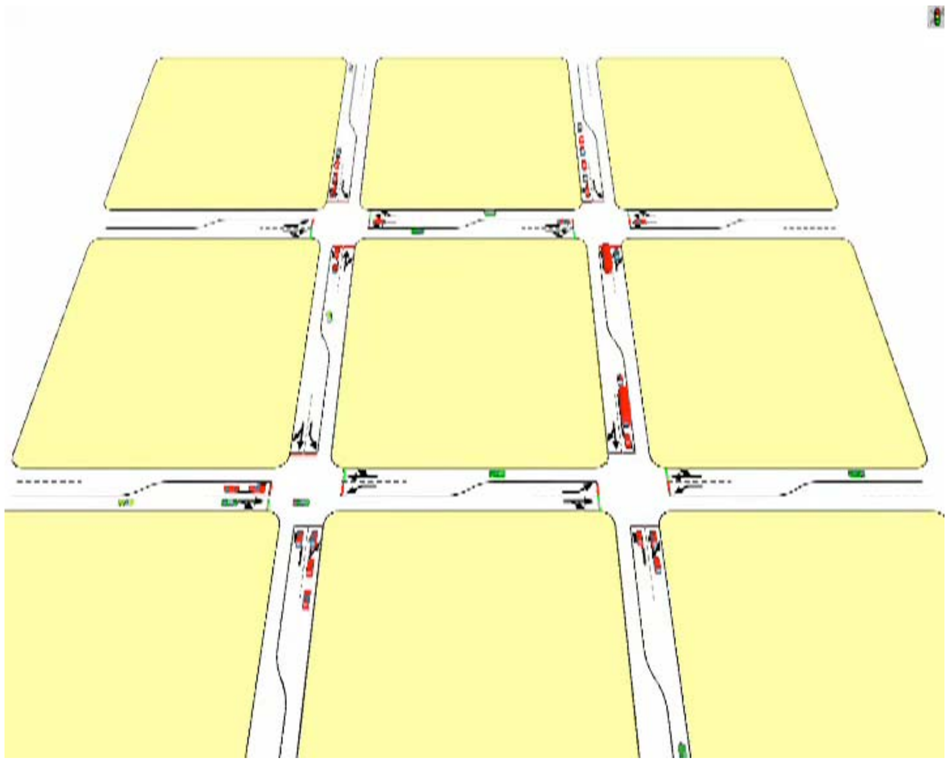


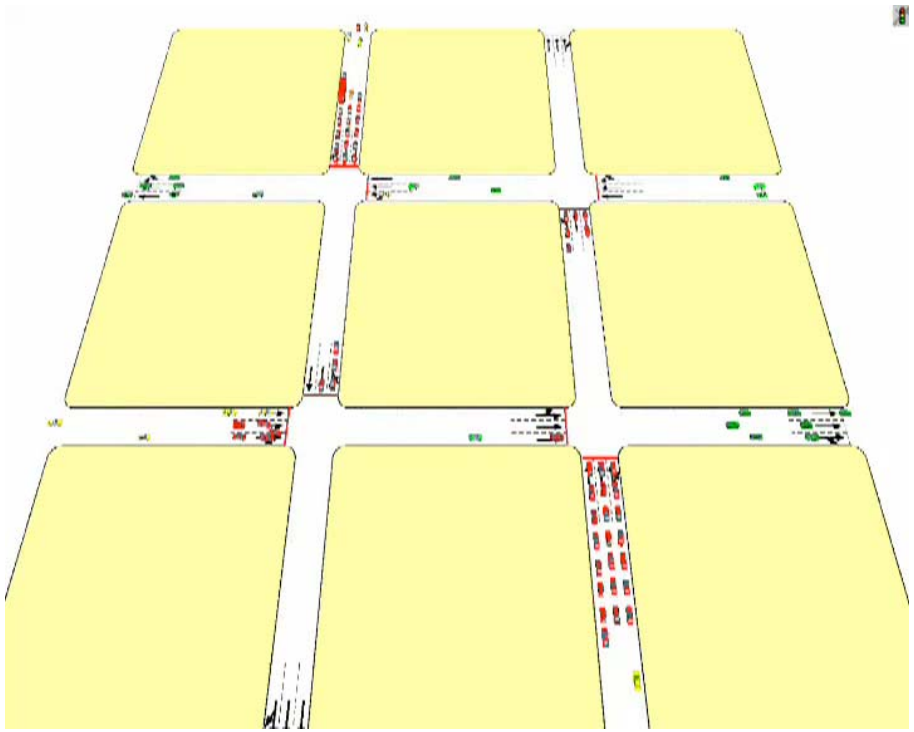
Reduction of Traffic Phases Means Increase of Capacity



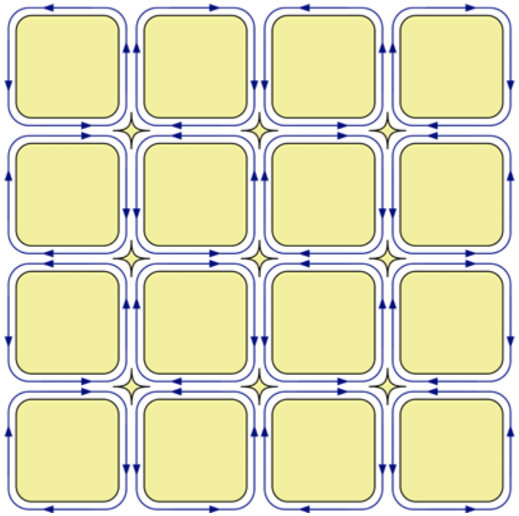
Reorganizing the Traffic Network

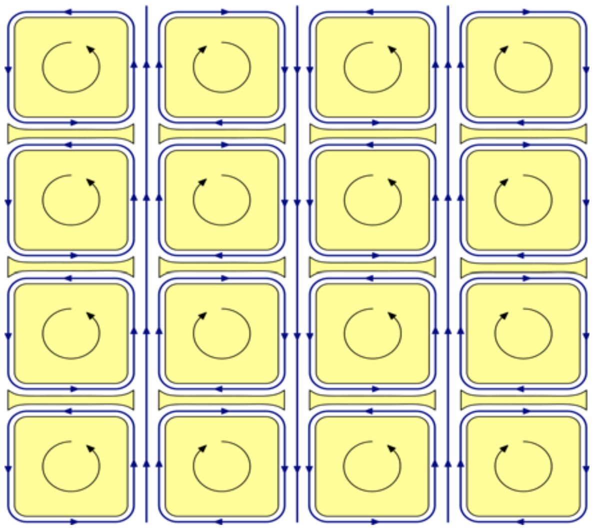


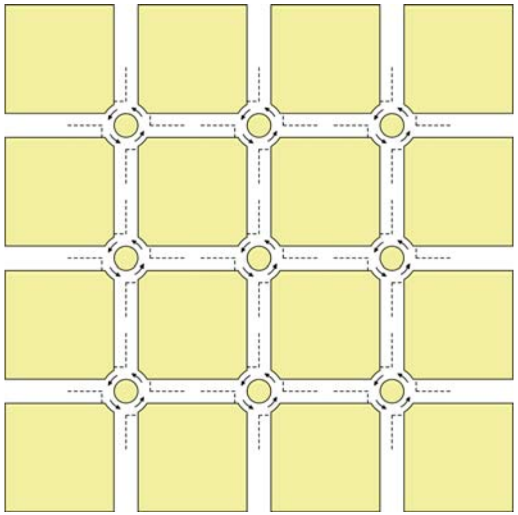


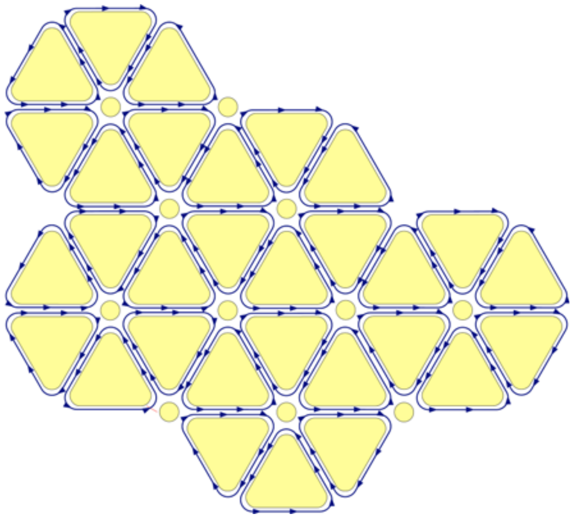


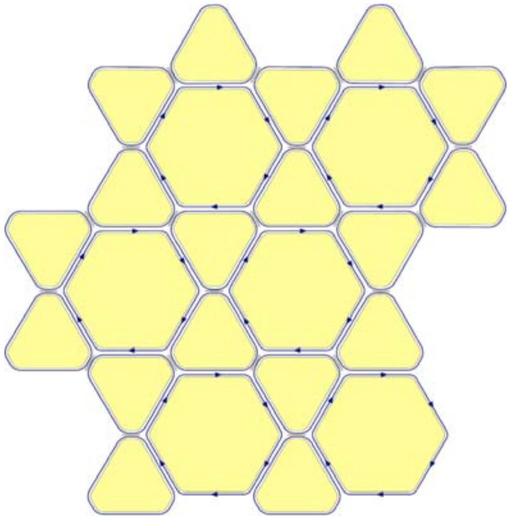
Intersection-Free Designs











Self-Organized Traffic Flow at Unsignalized Intersections

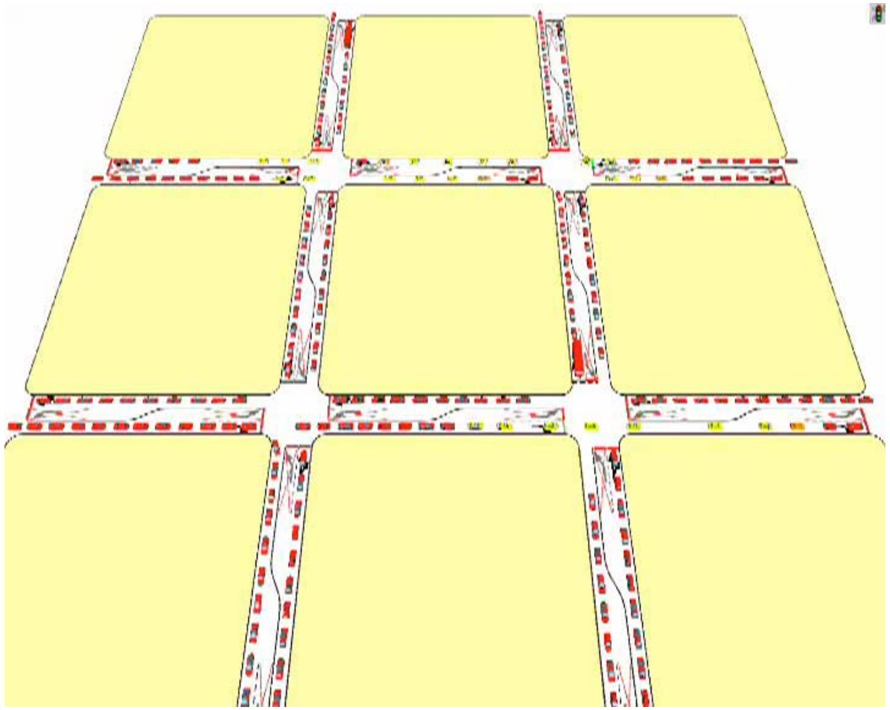
Operation Regimes of Traffic Light Scheduling

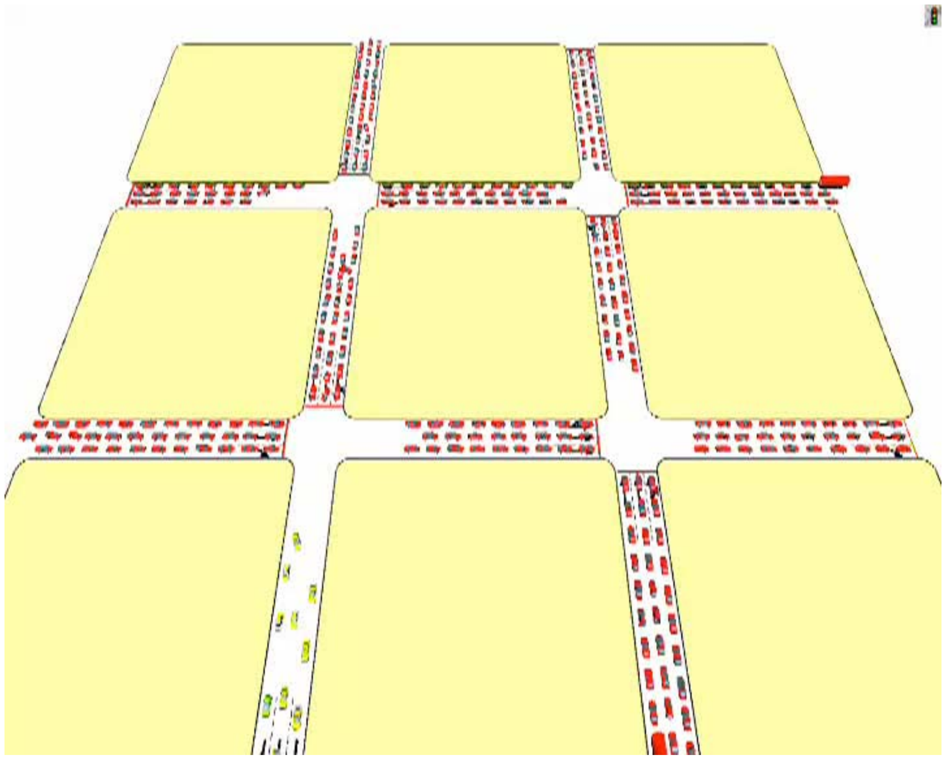
IV. Bubble Flow, Heavily Congested Gap Propagation Regime

- Demand considerably above capacity
- Almost all streets are more or less fully congested
- Gap propagation principle replaces vehicle propagation
- Goal is to avoid stopping of gap ("bubble propagation")
- Larger and moving gaps are given priority

Best in terms of throughput is an approximately half-filled system. The load/occupancy corresponding to the maximum throughput should not be exceeded. The use of access control with traffic lights is, therefore, recommended. This defines a kind of CONWIP strategy for traffic.

Gap Propagation Regime





Self-Organized Traffic Light Control

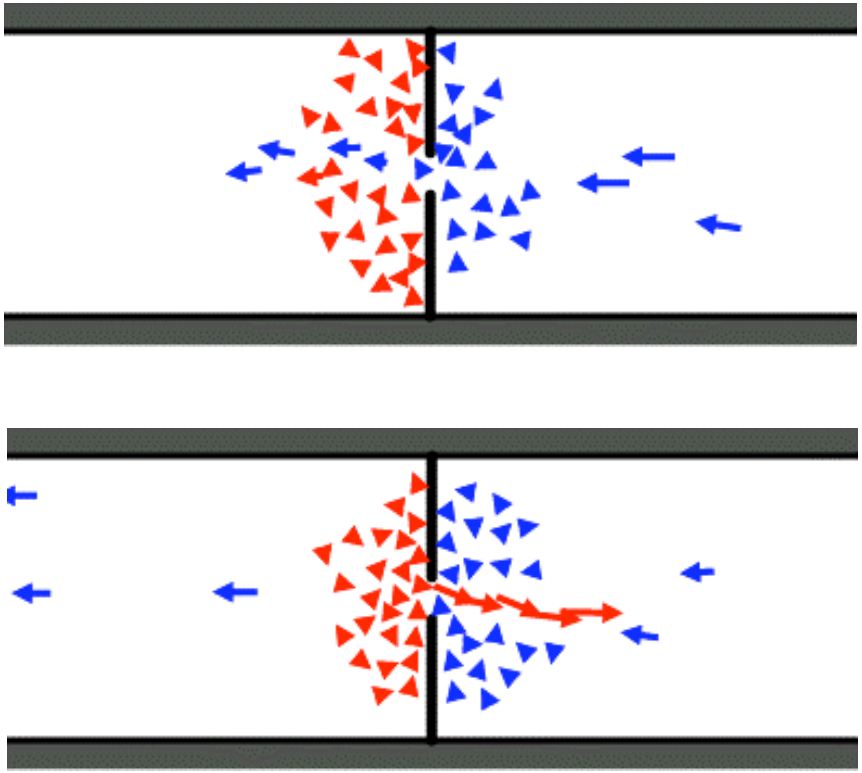
Objectives:

- Search for a self-organization principle that flexibly switches between the different operation regimes.
- In addition, it should optimize operation within each operation mode.
- Green waves should emerge as a result of coordination/ synchronization among neighboring traffic lights
- Goal function needs to take into account both travel times and throughputs

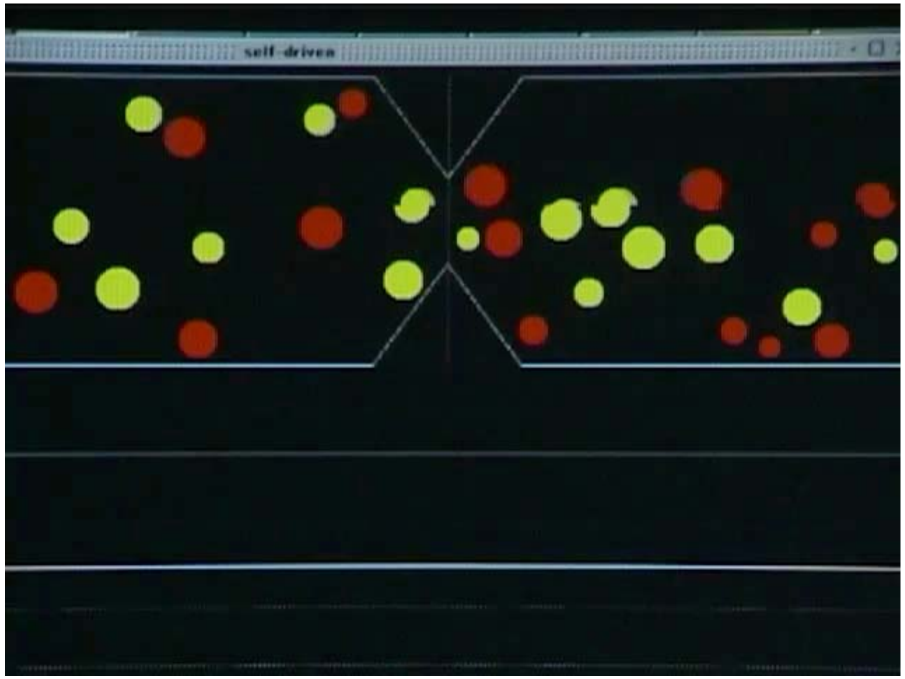
Expected Advantages:

- More flexible adaptation to the local, varying traffic situation
- Improved traffic light scheduling during situations such as accidents, building sites, failures of traffic lights, mass events, evacuation scenarios, etc.
- Increased robustness with respect to fluctuations and failures by decentralized control concept and collective intelligence approach

Self-Organized Oscillations at Bottlenecks and Synchronization

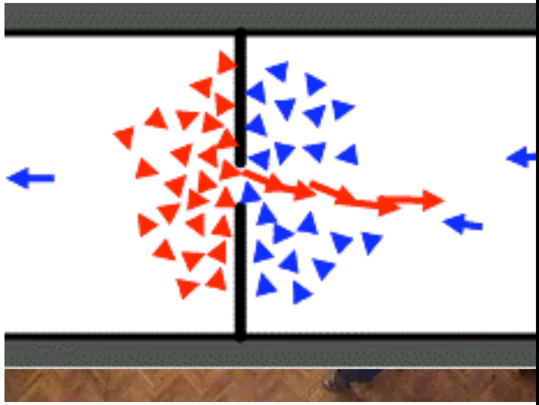


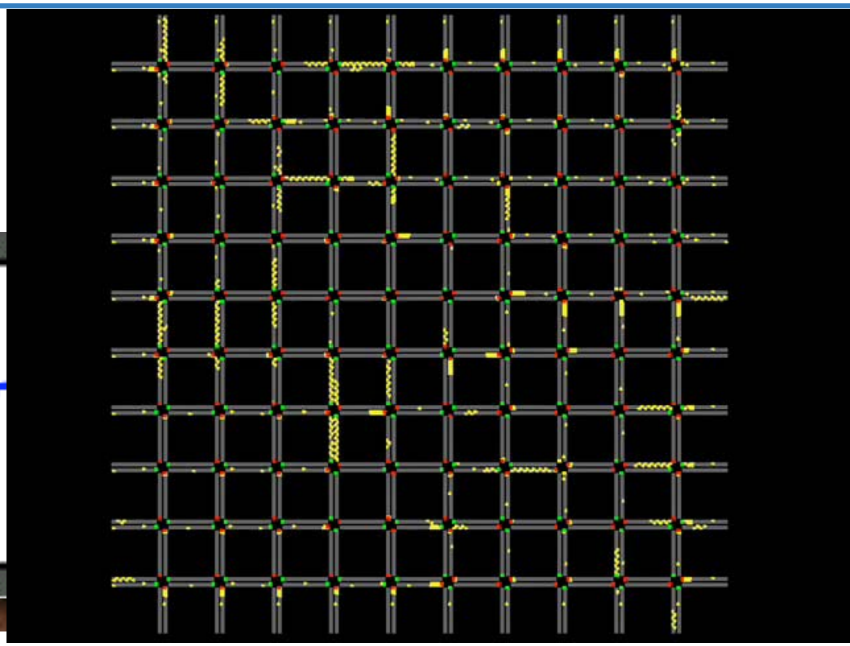
- Pressure-oriented, autonomous, distributed signal control:
  - Major serving direction alternates, as in pedestrian flows at intersections
  - Irregular oscillations, but 'synchronized'
- In huge street networks:
  - 'Synchronization' of traffic lights due to vehicle streams spreads over large areas

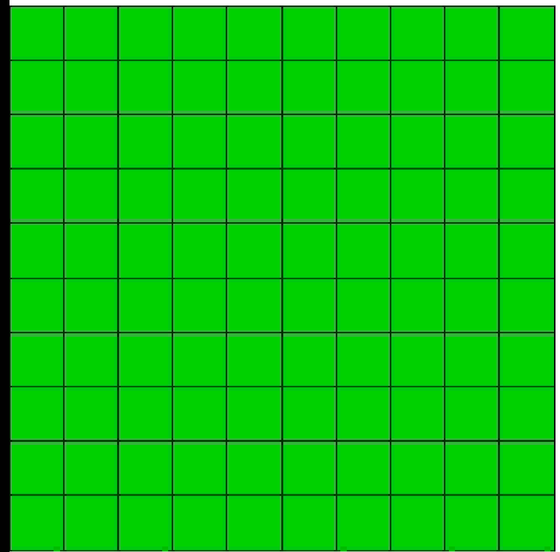


Decentralized Concept of Self-Organized Traffic Light Control

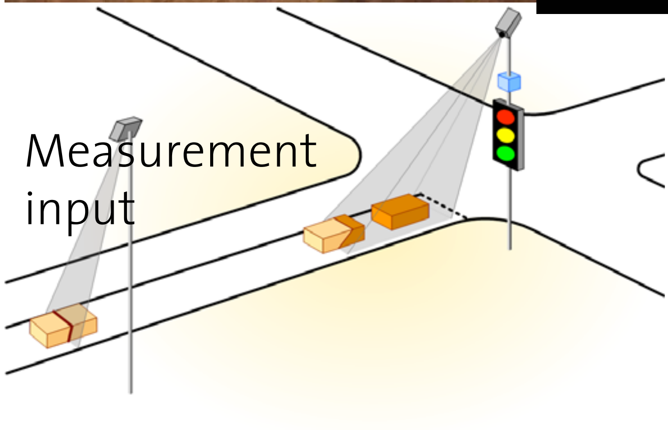
Inspiration: Self-organized oscillations at bottlenecks





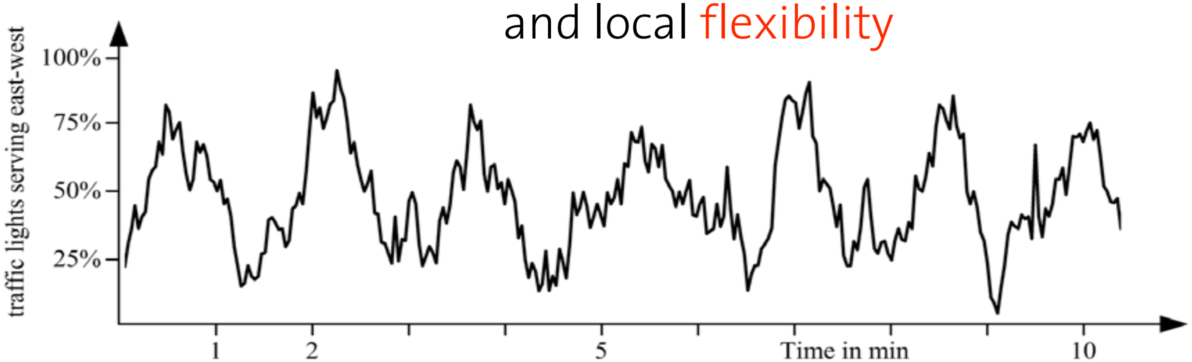


Measurement input



Published in *JSTAT* (2008)

Optimal compromise between coordination and local flexibility



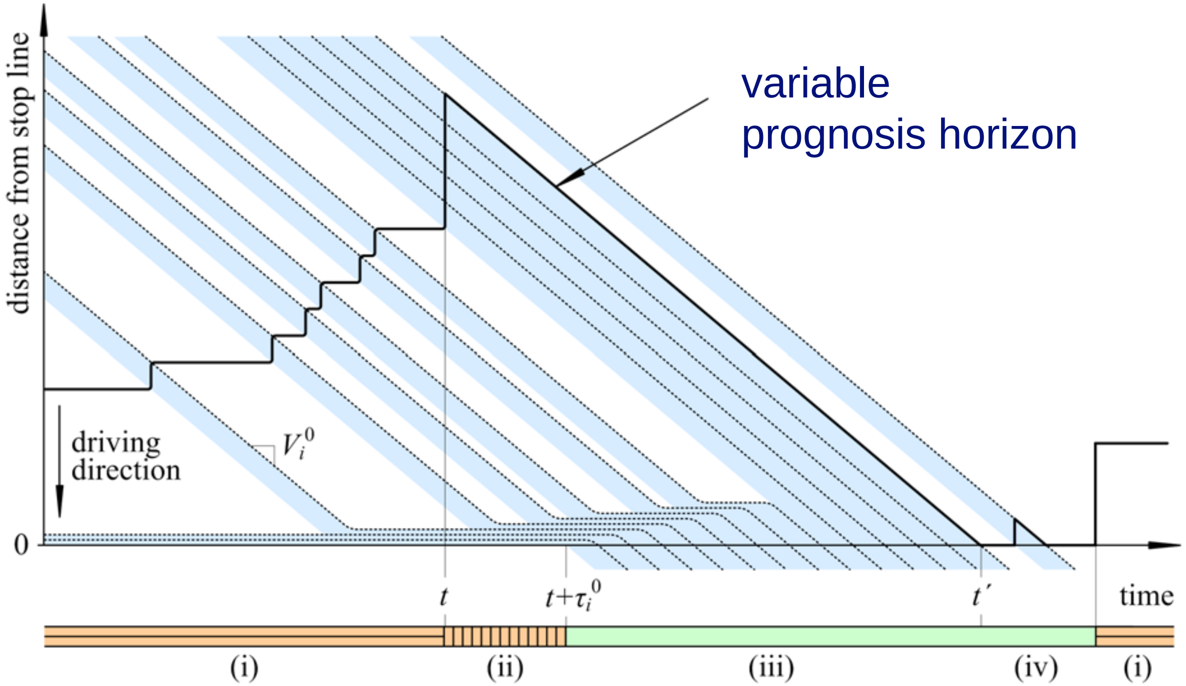
Properties of the Self-Organized Traffic Light Control

- Self-organized red- and green-phases
  - No precalculated or predetermined signal plans
  - No fixed cycle time
  - No given order of green phases
- Green phases depend on respective traffic situation on the previous *and* the subsequent road sections
  - Determined by actual queue length and delay times
  - Default state is red light
  - At light traffic conditions, single vehicles trigger green light
- Distributed, local control
  - Greater flexibility and robustness
  - Usage of sensors (optical, infrared, laser, ...)
  - No traffic control centre needed
- Pedestrians are handled as additional traffic streams
- Public transport may be treated as vehicles with a higher weight

Short-Term Prognosis of Vehicles Arriving

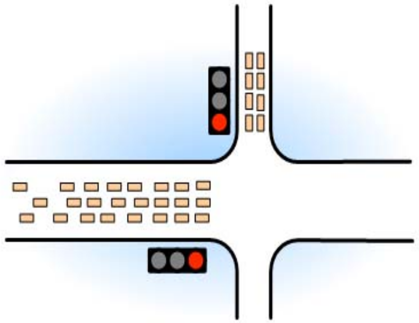
A fully adaptive traffic light operation means:

1. using decentralized methods
2. having limited prognosis horizons
3. having feedbacks via network loops, which are likely to cause instabilities

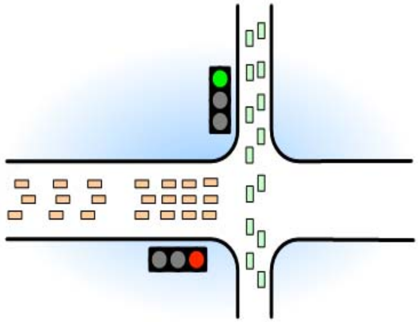


Local Optimization by Assigning Priorities

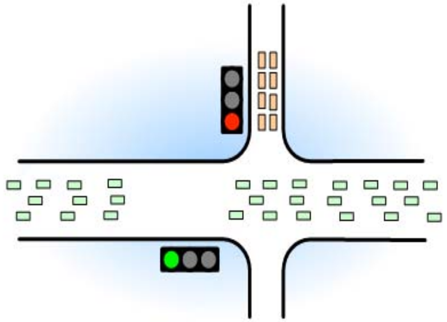
What queue
to serve first?



When to interrupt
a service process?



What time gaps
are acceptable?



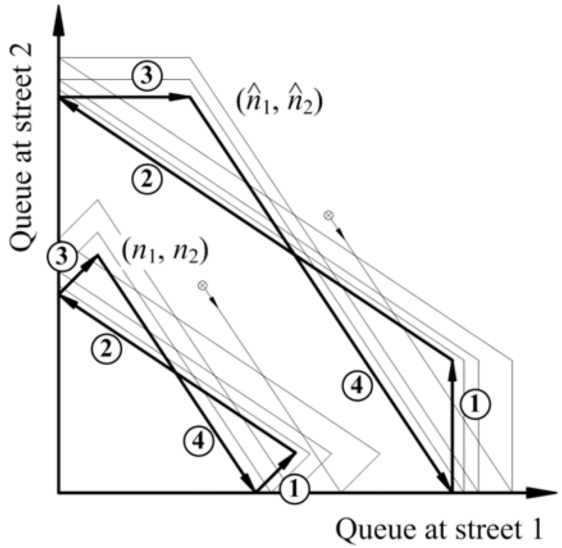
We were able to derive a priority index π,
which is optimal in each of these scenarios:

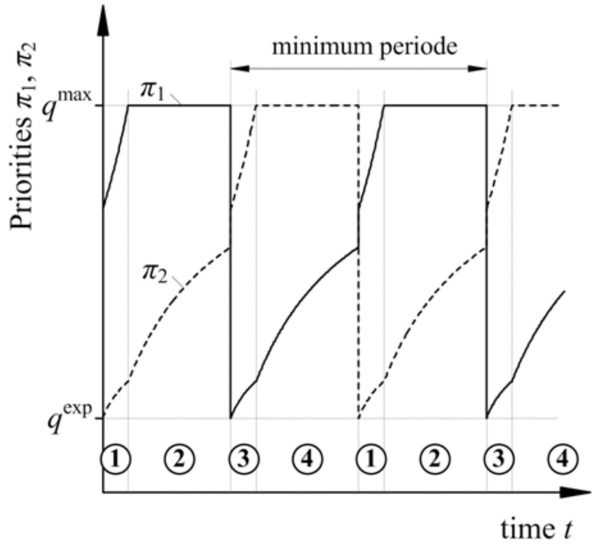
$$\sigma = \arg\ \max_i \{\pi_i \,|\, \pi_i > 0\}$$

An optimizing traffic light control results, when serving the road with highest priority.

Behavior of the Optimizing Controller in Time

For constant arrival rates, we find an exponential convergence to an optimal limit cycle.





Flexible scheduling for random arrivals:

(nw.avi) (iso.avi)

Because of the limited optimization horizon, instabilities can not be excluded!

(instab.avi) (art.avi)

Network-Wide Stability

Improved control strategy:

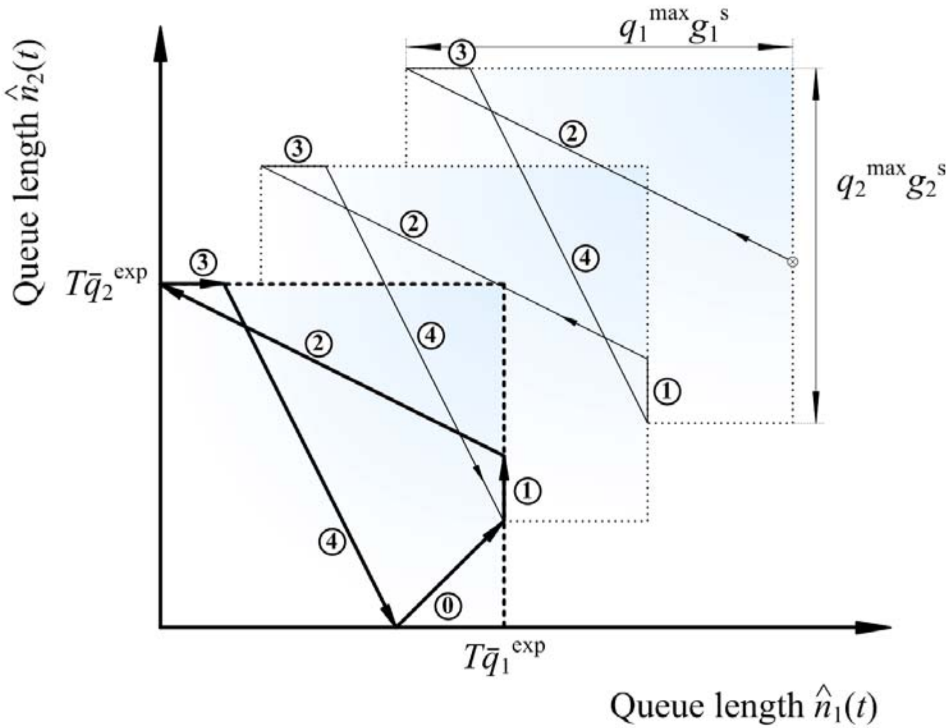
"Only switch to green, if at least a critica number of vehicles can be served. Otherwise stay on red."

Critical value can be set such that each street is served once within a desired time window.

This leads to minimum switching delays

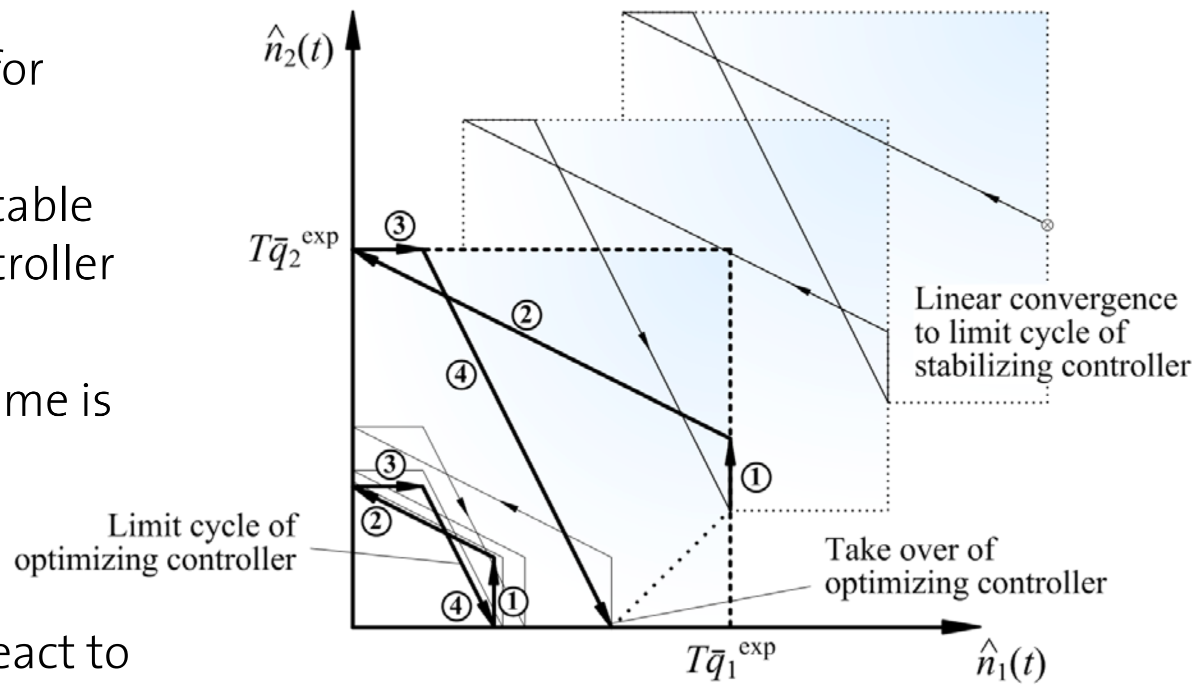
(stab.avi)

Linear convergence to a limit cycle



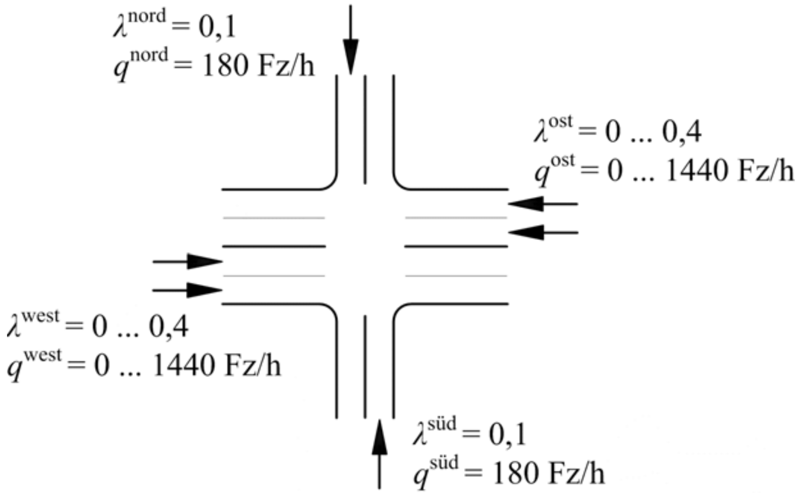
Combination of an Optimizing and a Stabilizing Controller

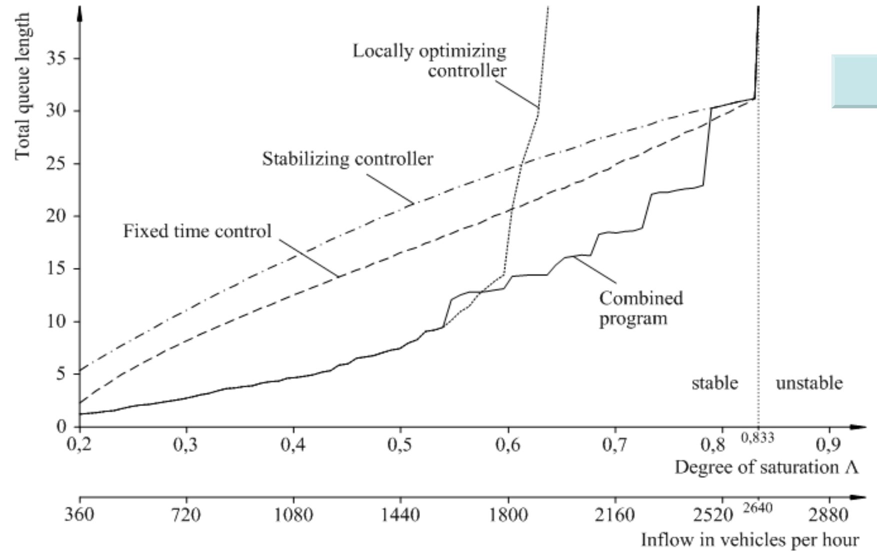
- The stabilizing controller guarantees a minimum service to each traffic stream.
- The remaining time is used for local optimization.
- If the optimizing regime is stable itself, then the stabilizing controller never interferes.
- Otherwise, if optimizing regime is unstable, then the stabilizing controller makes occasional corrections.
- Since both controllers only react to local arrivals, the resulting behavior is fully adaptive and also anticipative.



Simulation Study: Isolated Intersection (1)

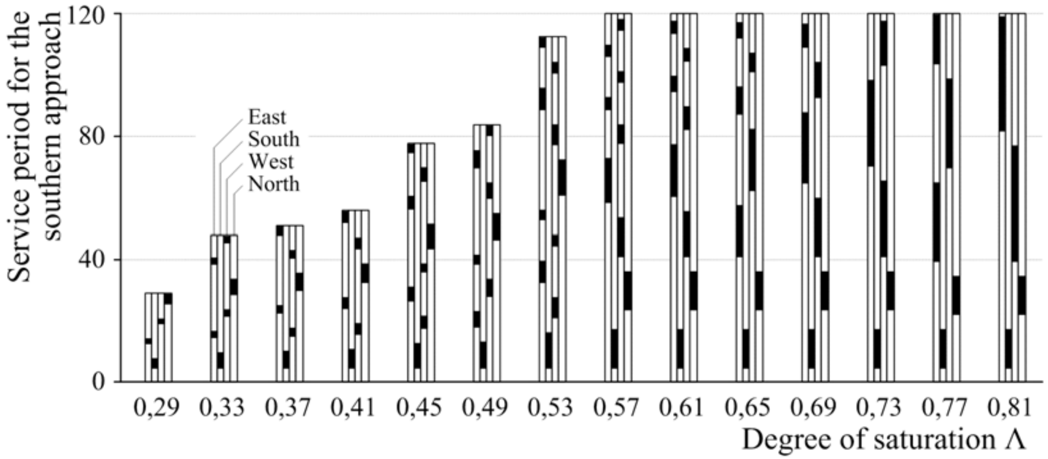
With constant arrival rates:





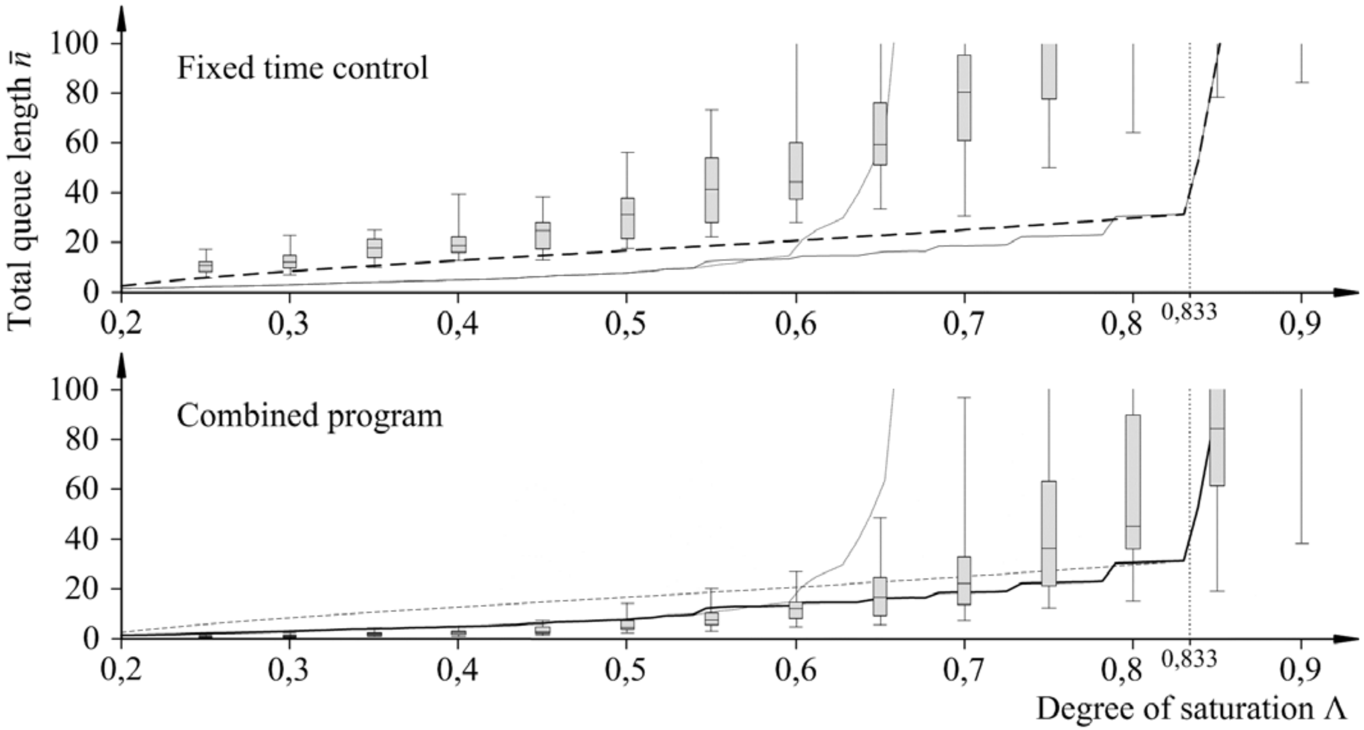
The switching sequence adapts to the arrival patterns.

We observe a **flexible switching** regime with **maximum red-times**.



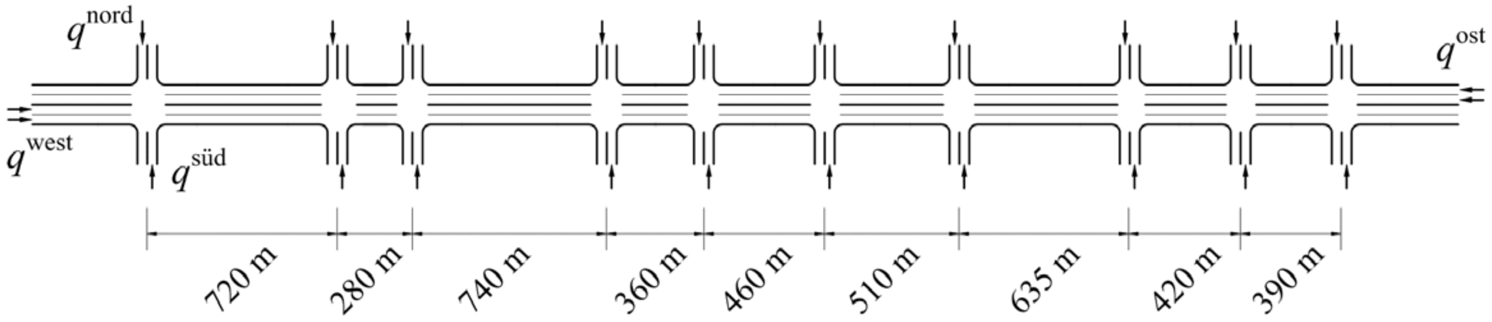
Simulation Study: Isolated Intersection (2)

With stochastic arrivals:

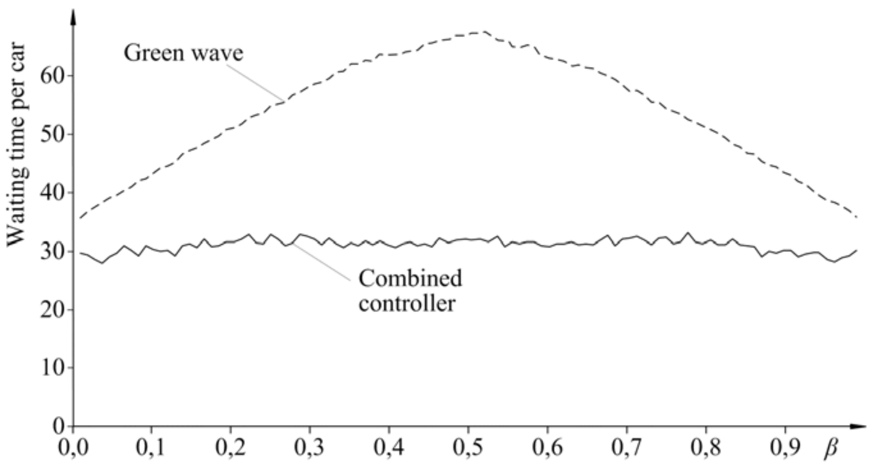


Due to the flexibility, we observe a reduction in both, the total **waiting time** and its **variance**.

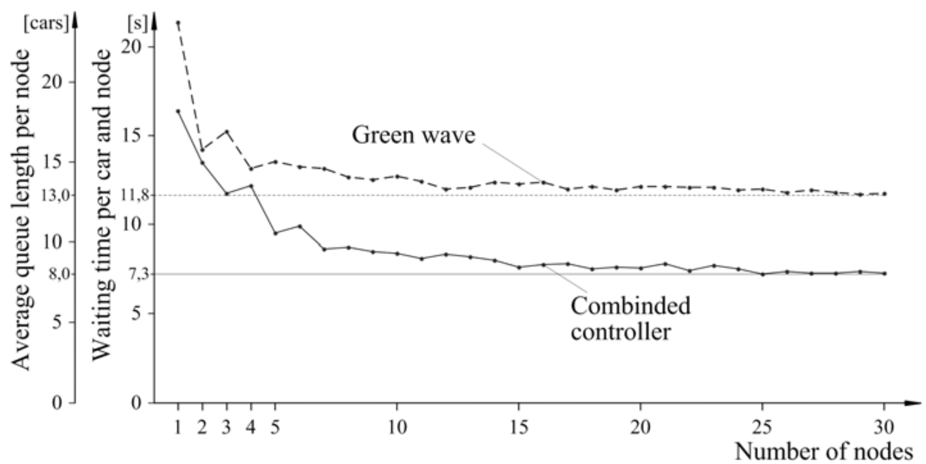
Simulation Study: Coordination along an Arterial (1)



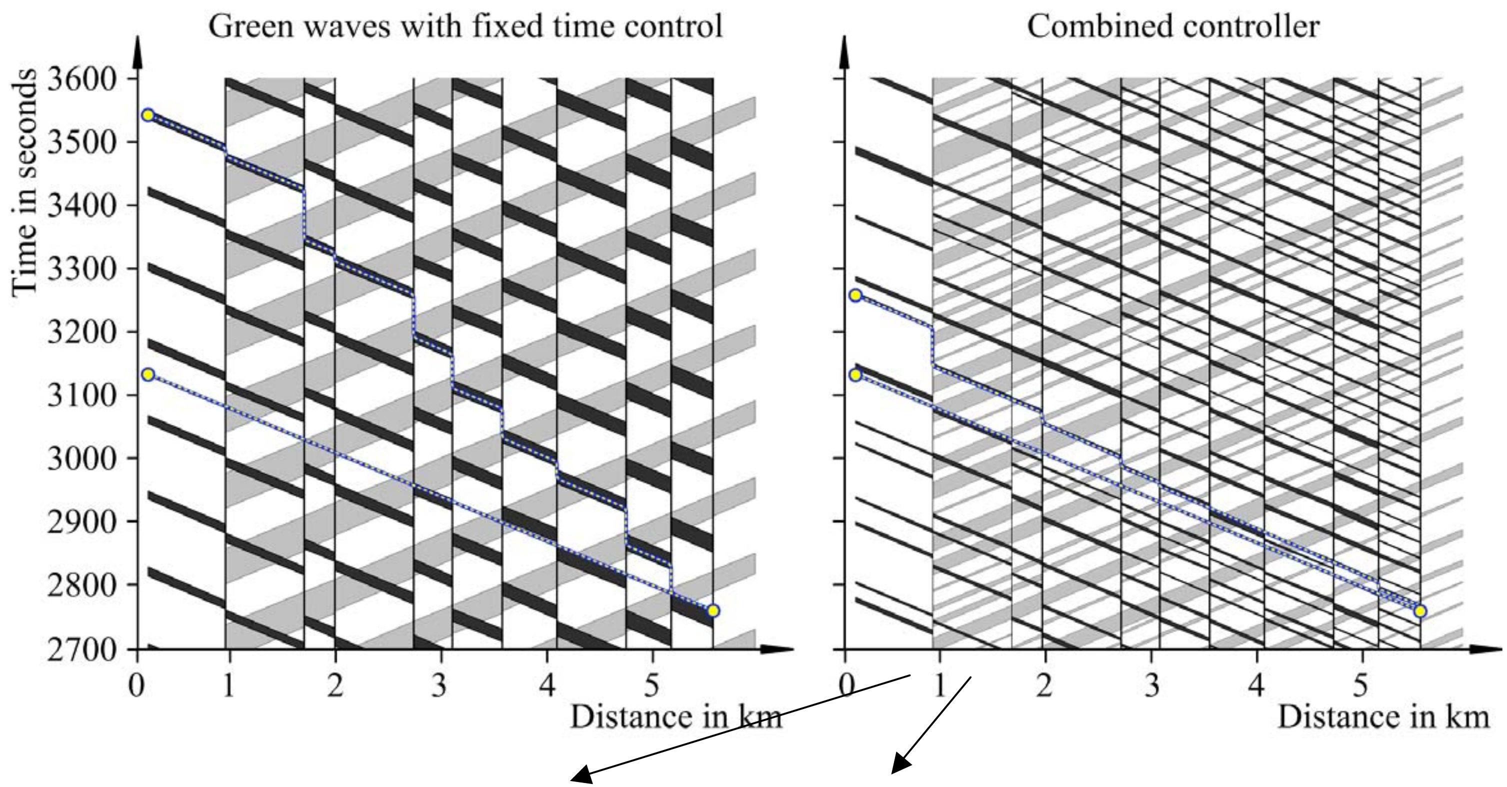
Varying the direction of the main flow



Varying the number of nodes along the arterial



Simulation Study: Coordination along an Arterial (2)



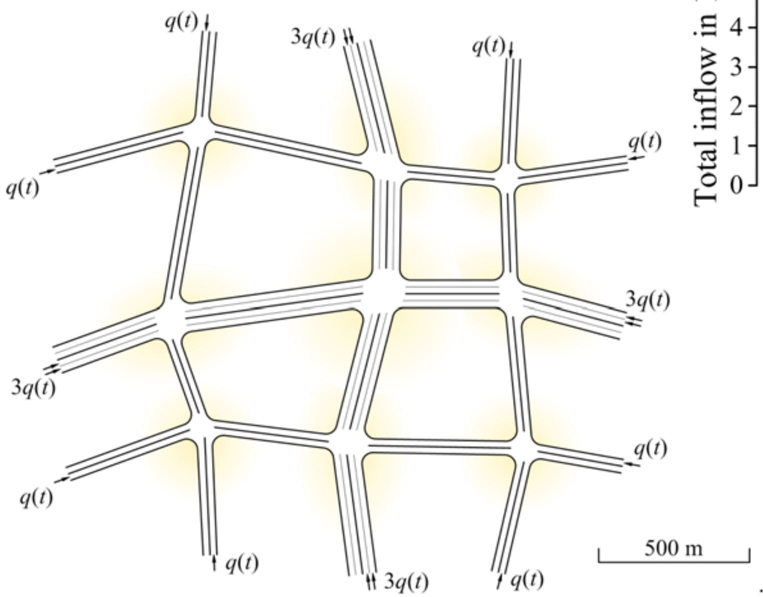
Irregular switching patterns are equalizing irregular traffic patterns, and thereby minimizing waiting times.

Principles:

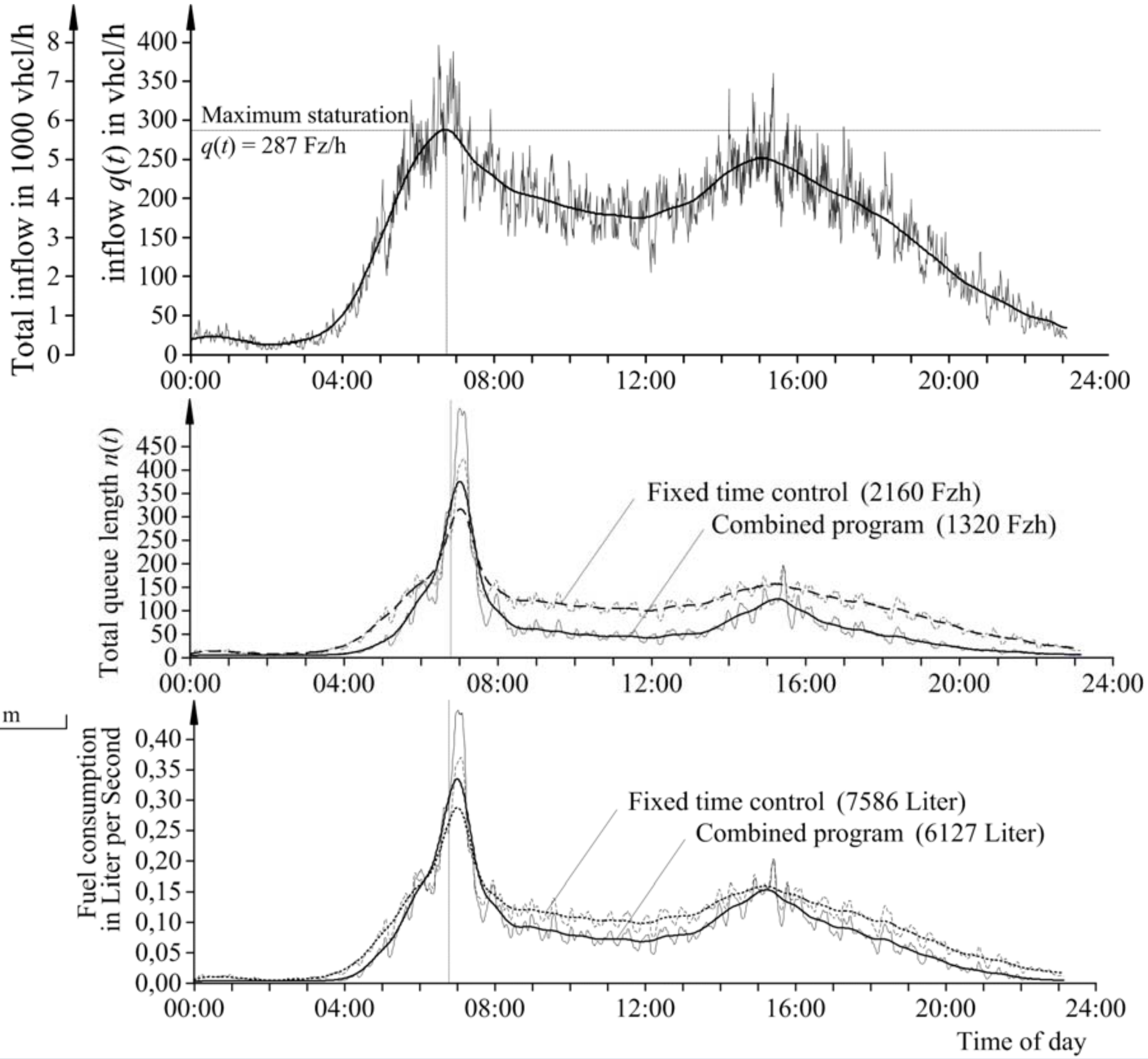
1. Platoon formation
2. Flexible scheduling of platoons
3. Minor streams are served during time gaps.

Coordination in a Network

Simulated network:

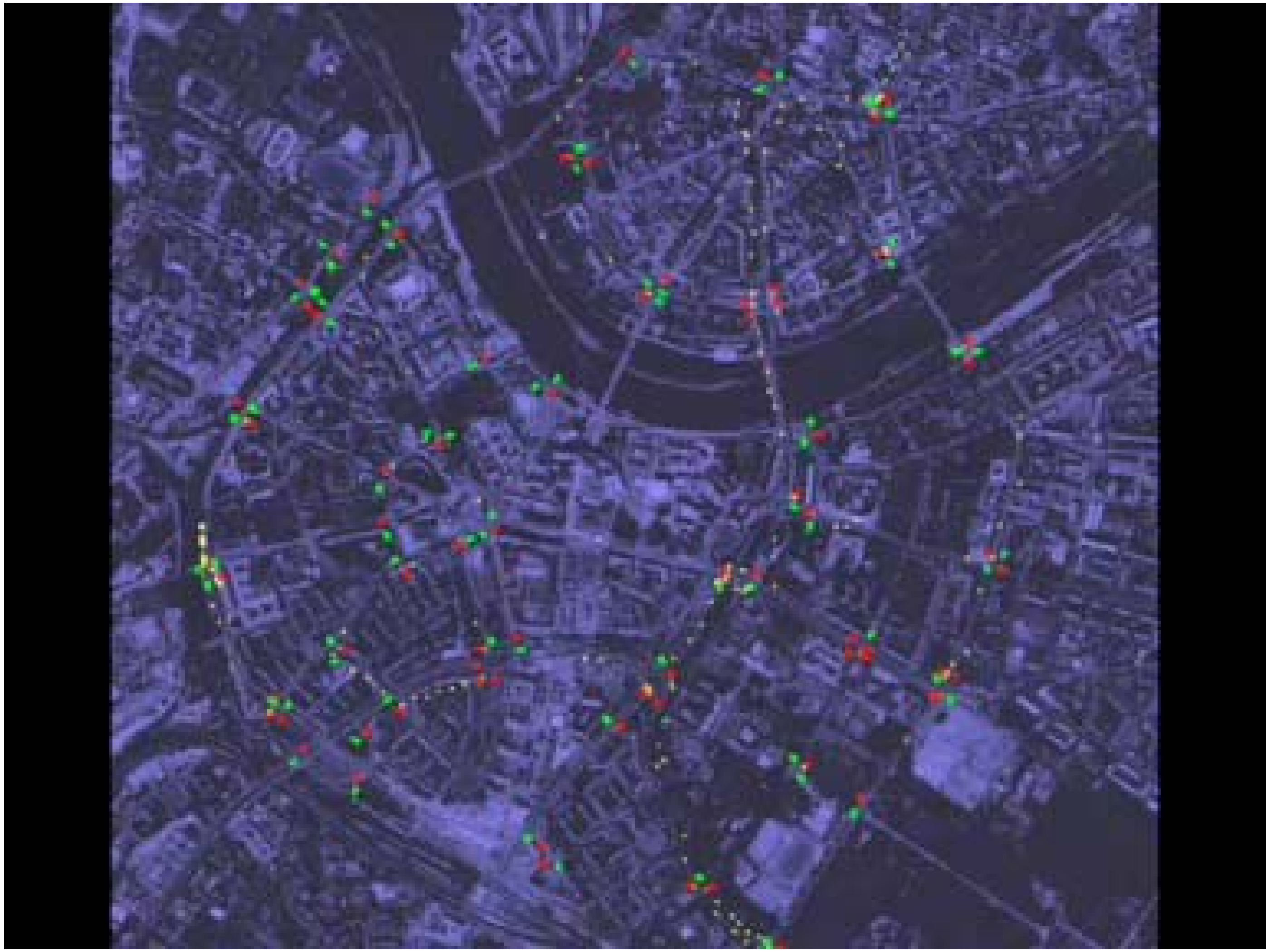


Traffic demand is specified with empirical data:

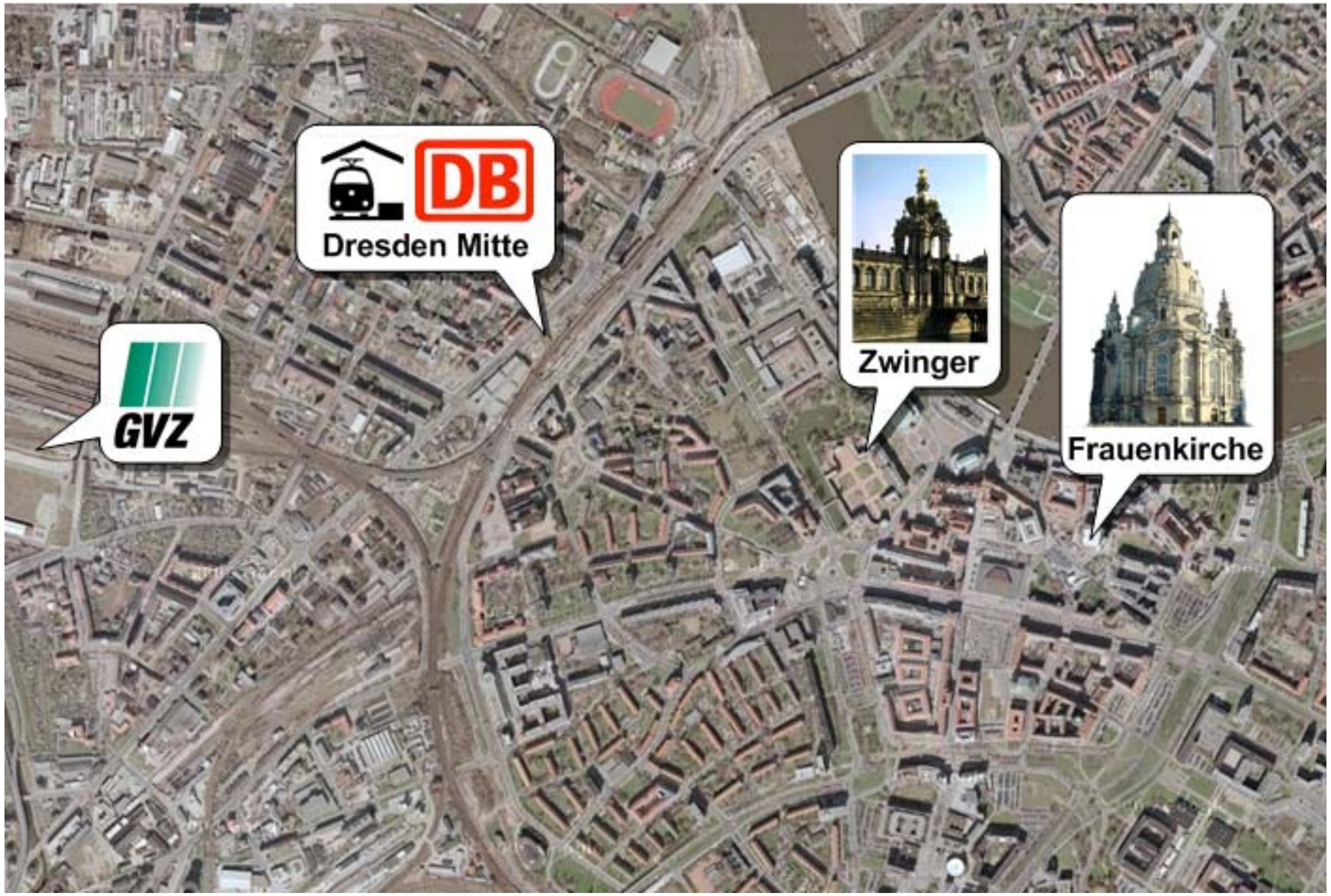


Application Example: City Center of Dresden

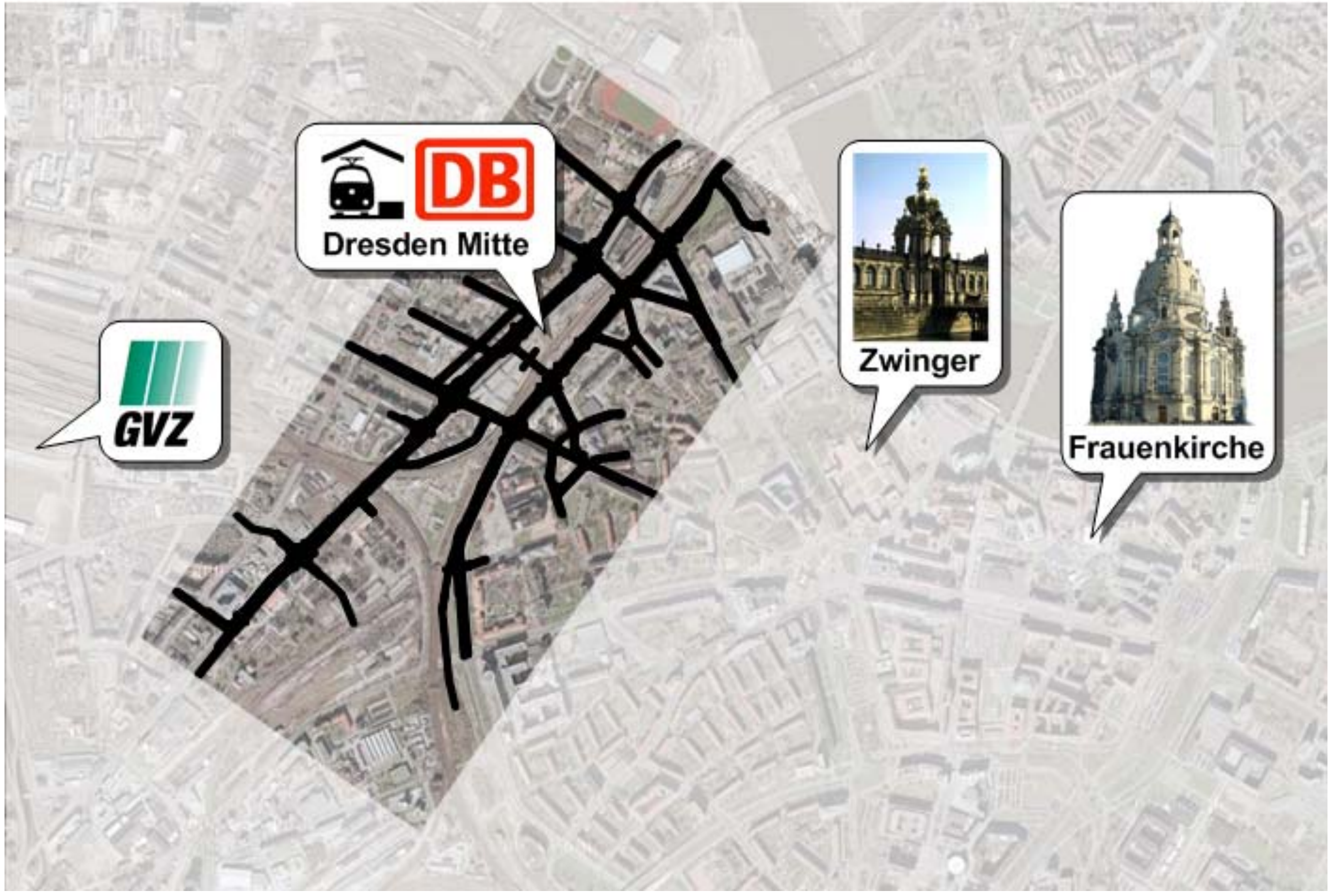
Simulation "Pirnaischer Platz"



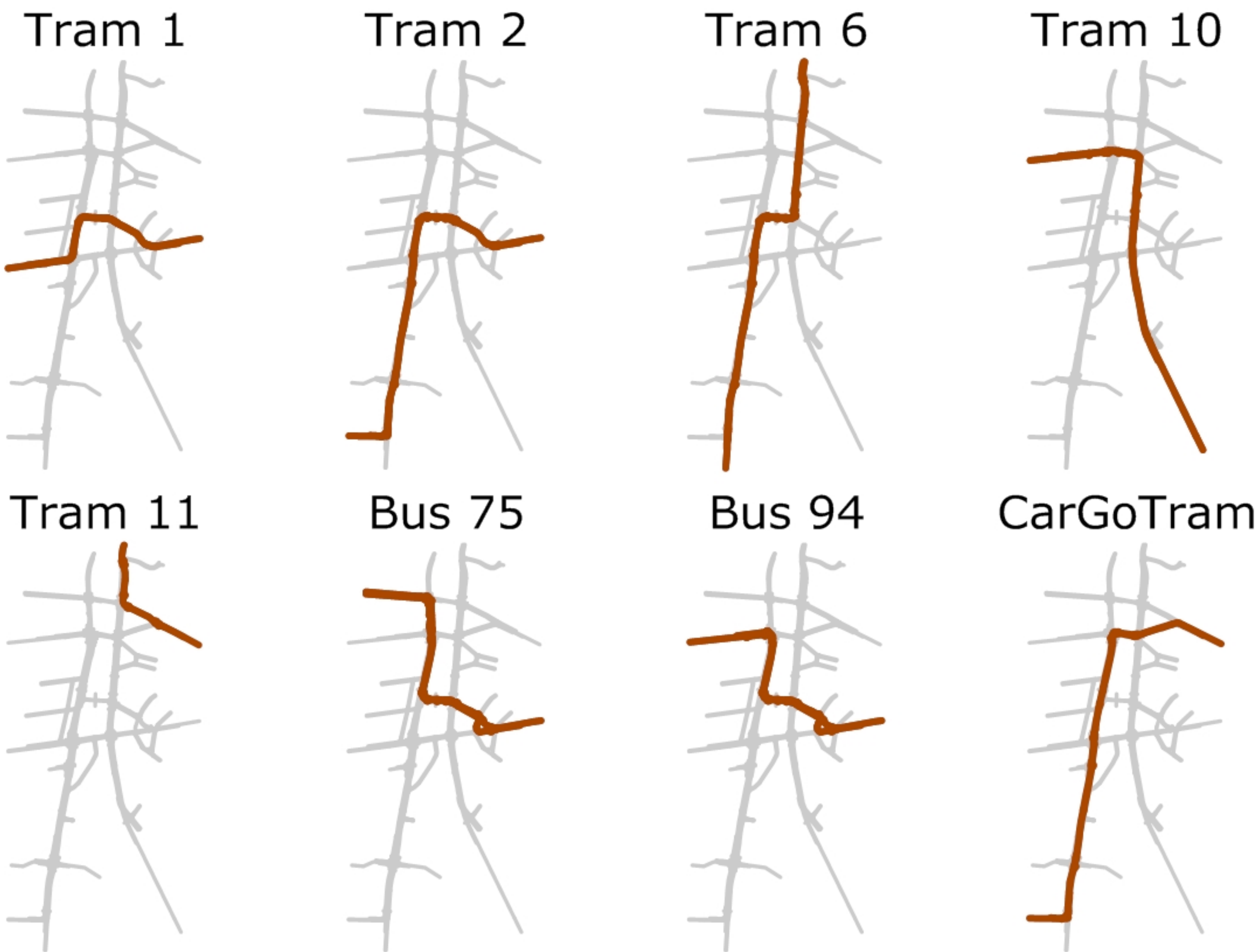
Towards Self-Organized Traffic Light Control in Dresden



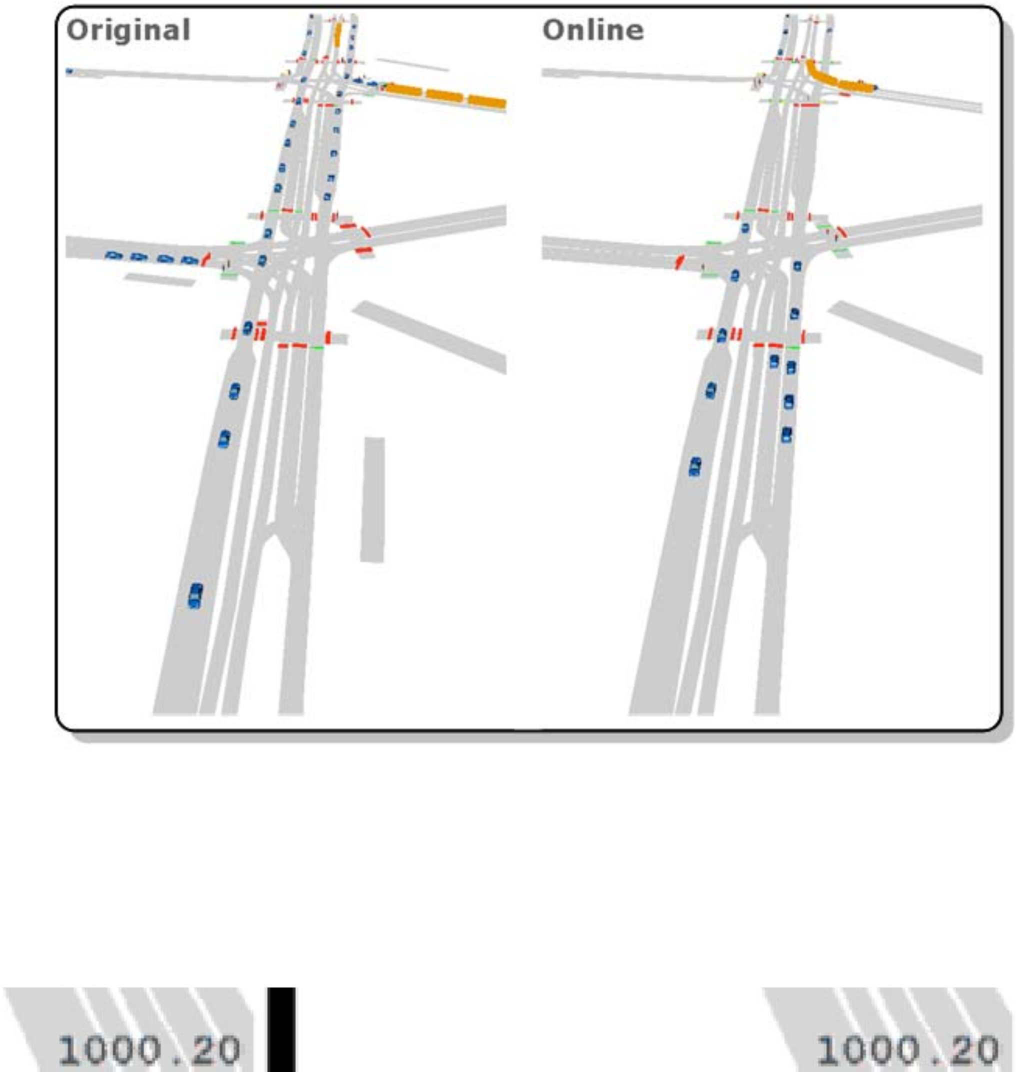
The Measurement and Control Area



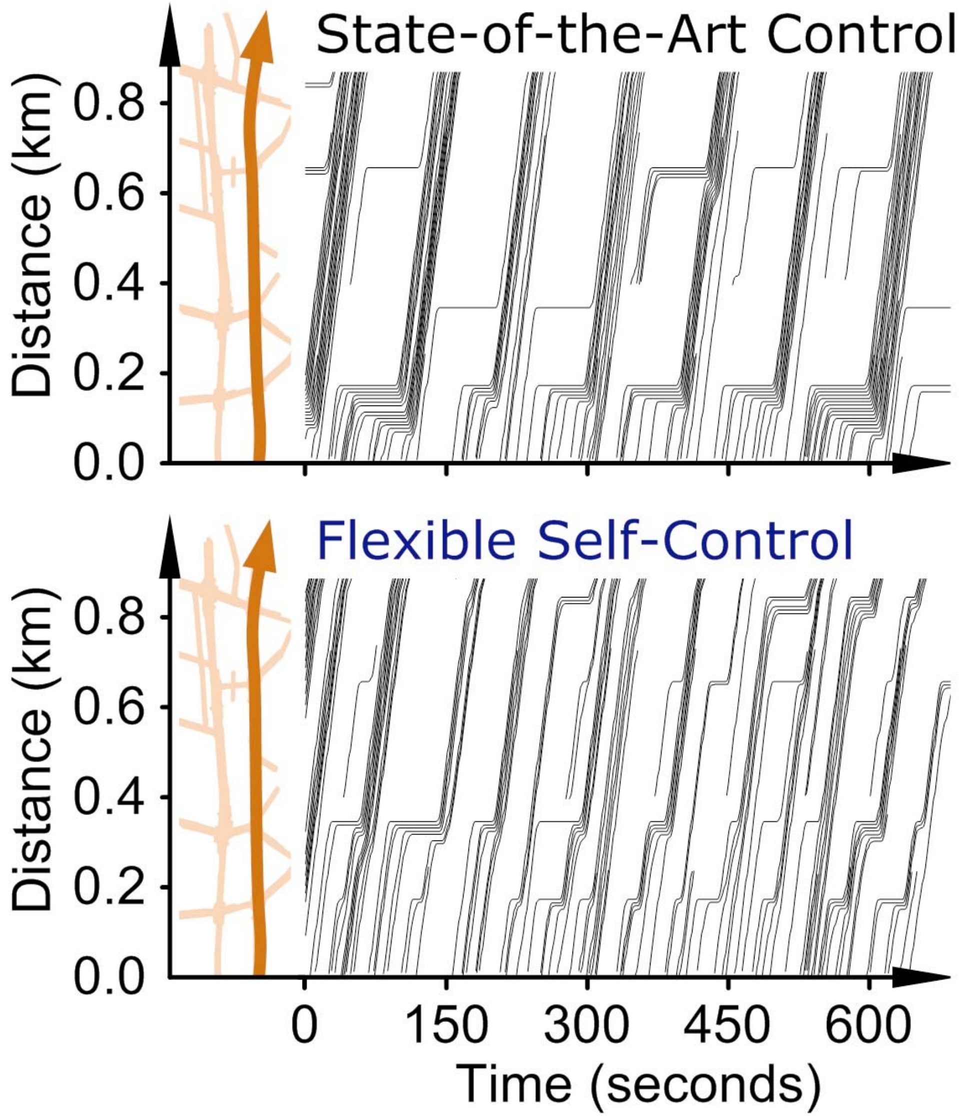
Disturbance of Traffic Coordination by Bus and Tram Lines



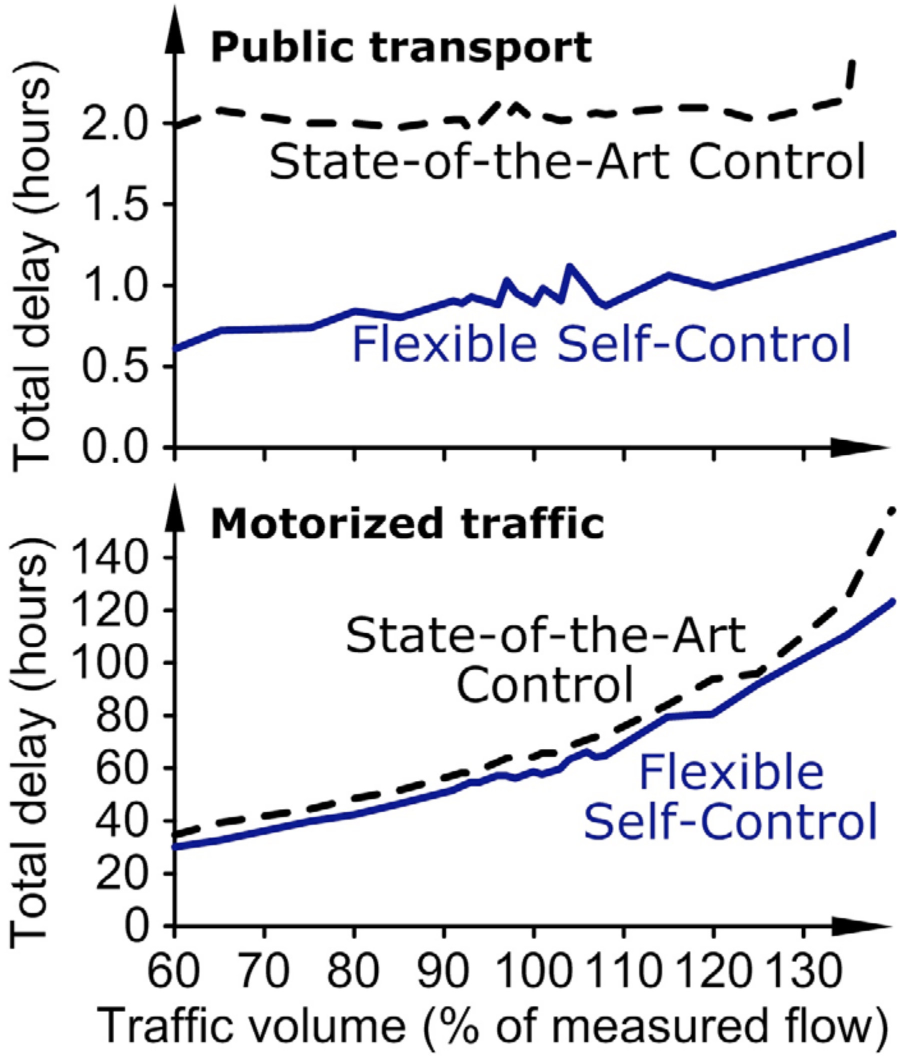
Comparison of Current and Self-Organized Traffic Light Control



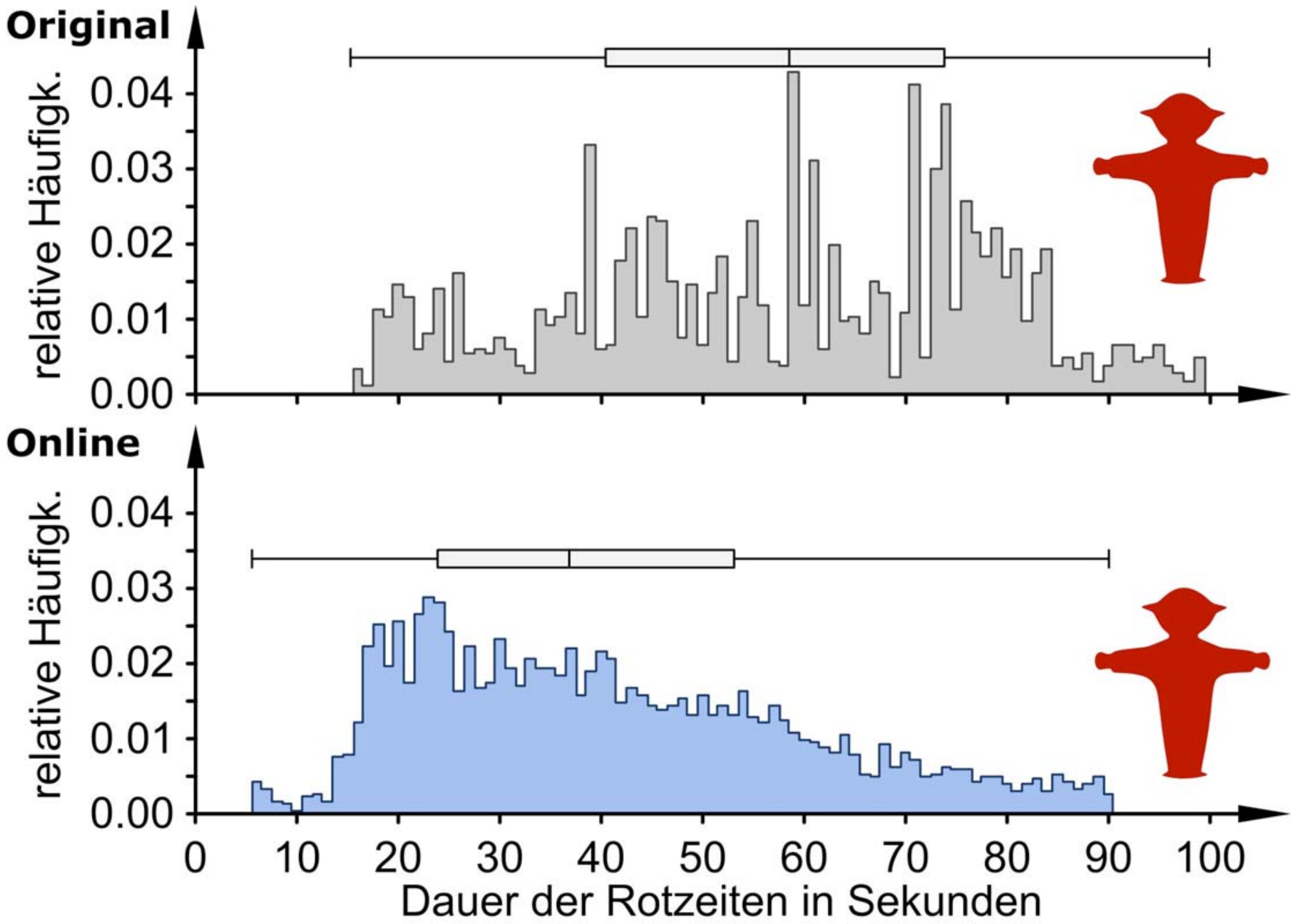
Synchronize Traffic by Green Waves or Use Gaps as Opportunities?



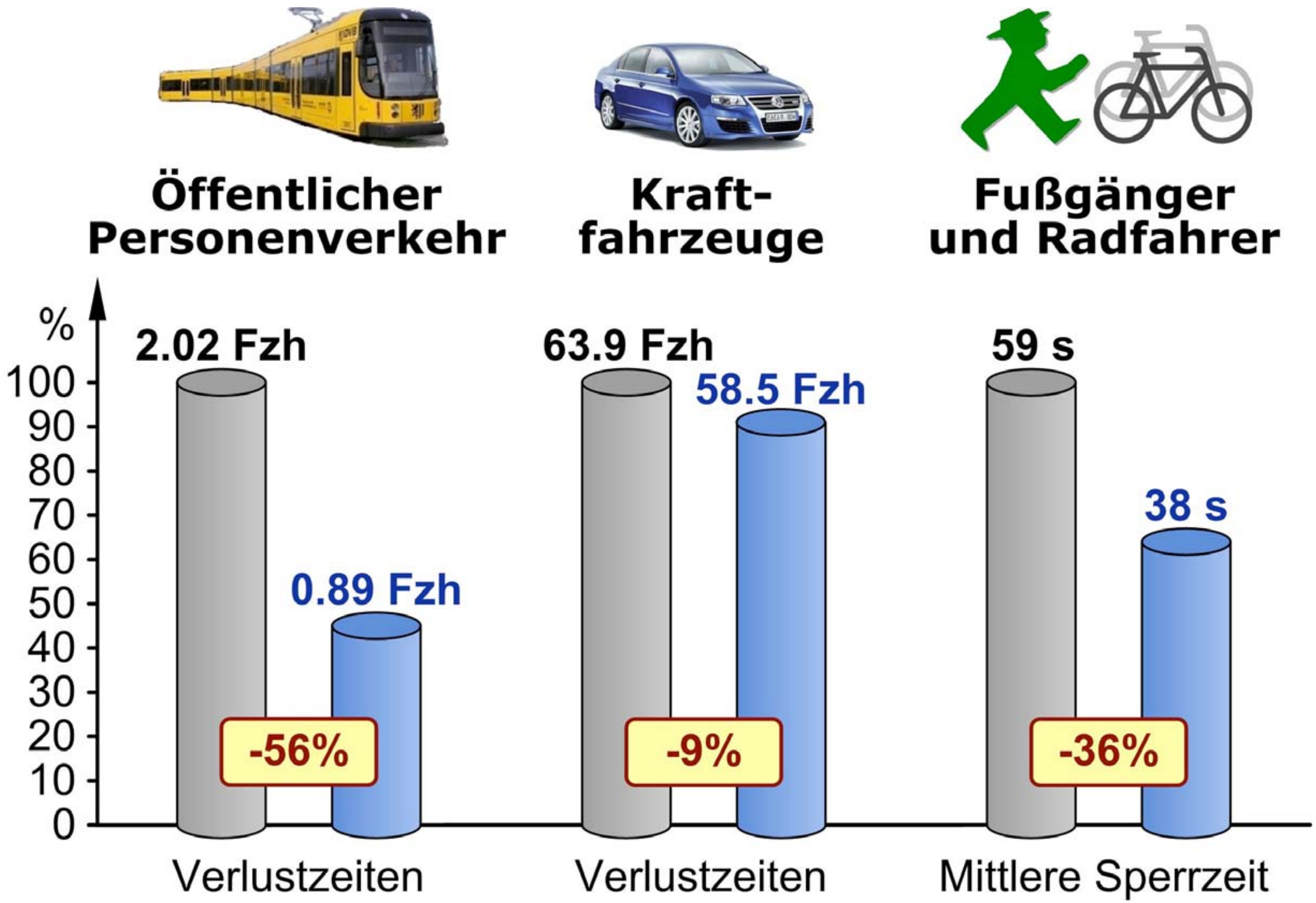
Performance in Dependence of the Traffic Volume



Red Time Distribution for Pedestrians

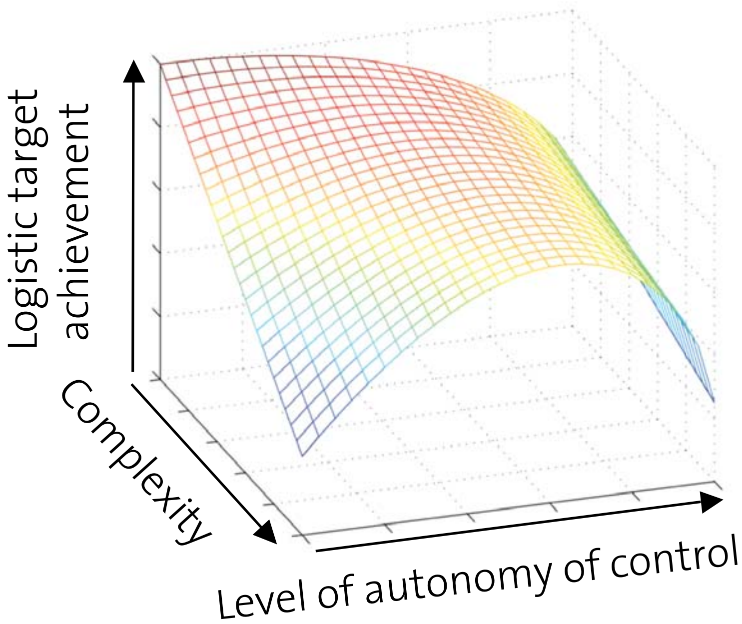


Gain in Performance



Centralized Control and Its Limits

- Advantage of centralized control is large-scale coordination
- Disadvantages are due to
  - vulnerability of the network
  - information overload
  - wrong selection of control parameters
  - delays in adaptive feedback control
- Decentralized control can perform better in complex systems with heterogeneous elements, large degree of fluctuations, and short-term predictability, because of greater flexibility to local conditions and greater robustness to perturbations



(Windt, Böse, Philipp, 2006)

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Thank you for your interest!

Any Questions?