ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

# Self-Organization and Self-Optimization of Traffic Flows on Freeways and in Urban Networks

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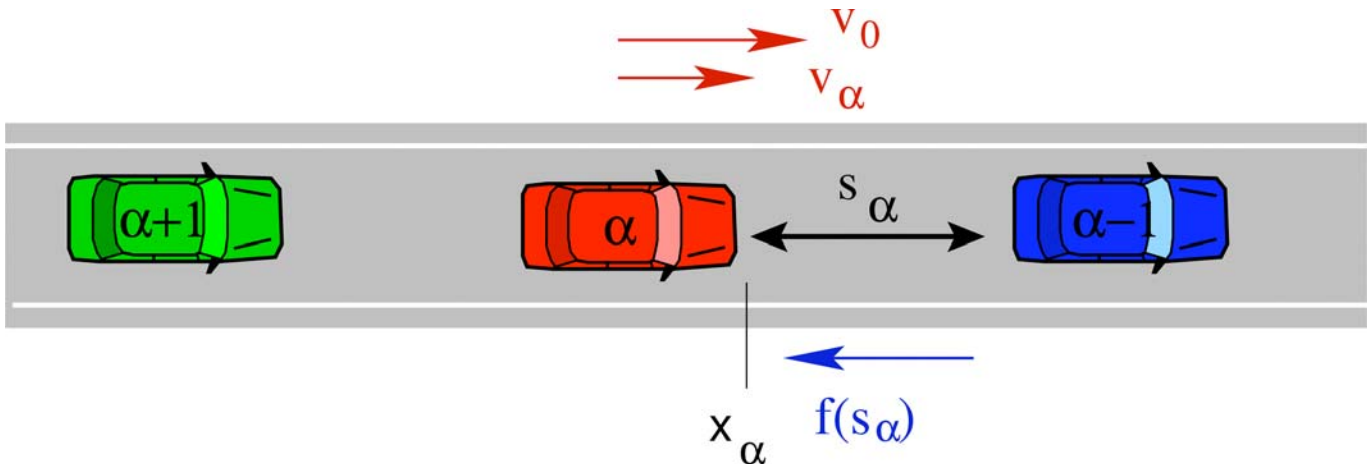
with Amin Mazloumian, Stefan Lämmer, Reik Donner, Johannes Höfener, Jan Siegmeier, …

# The Intelligent-Driver Model (IDM)



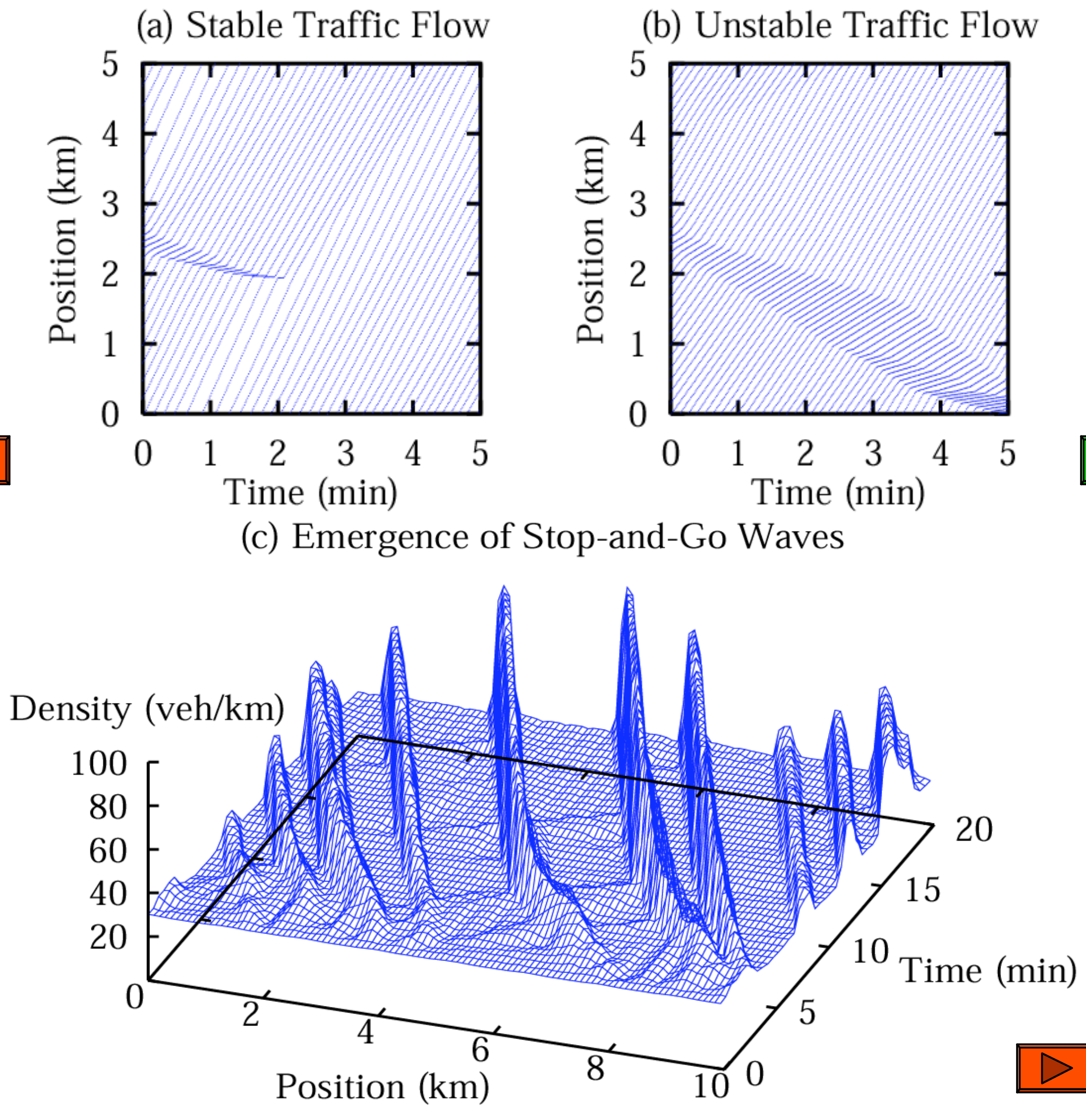

- Equations of motion:

$$\dot{x}_\alpha = v_\alpha,$$
$$\dot{v}_\alpha = a \underbrace{\left[1 - \left(\frac{v_\alpha}{v_0}\right)^\delta}_{\text{Beschleunigung}} \underbrace{- \left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha}\right)^2\right]}_{\text{Bremsverzögerung}}$$

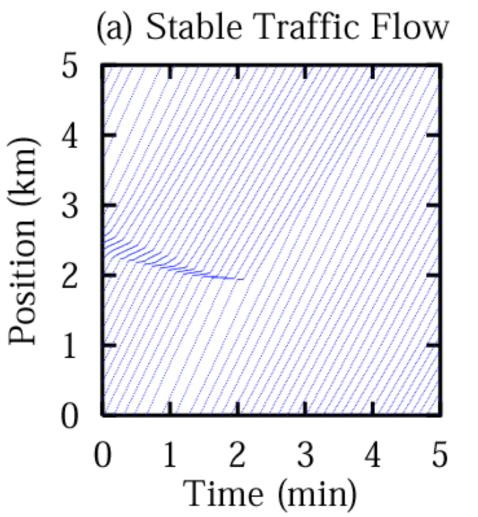
- Dynamic desired distance

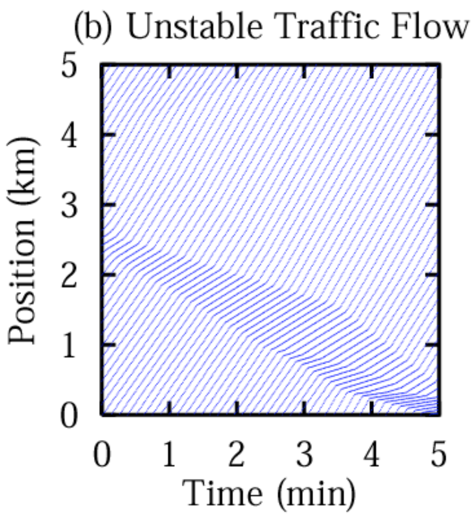
$$s^*(v, \Delta v) = \underbrace{s_0}_{\substack{\text{Mindest-}\\ \text{abstand}}} + \underbrace{vT}_{\substack{\text{“Sicherheits”-}\\ \text{abstand}}} + \underbrace{\frac{v \Delta v}{2\sqrt{ab}}}_{\substack{\text{dynamischer}\\ \text{Teil}}}$$

# Instability of Traffic Flow



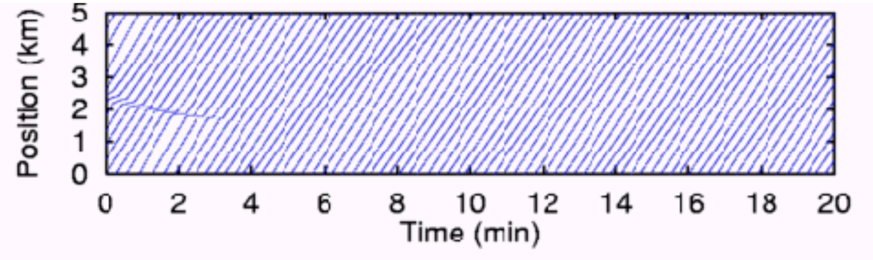
# Instability of Traffic Flow

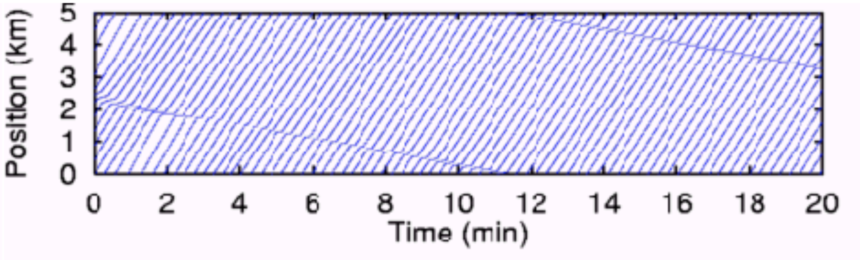



Source: Sugiyama et al.

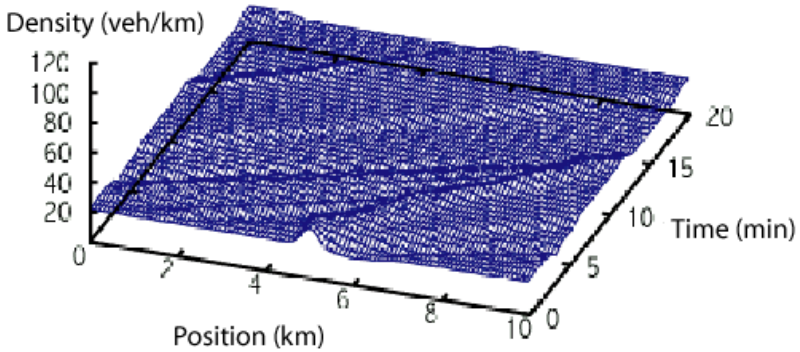
# Metastability of Traffic Flow

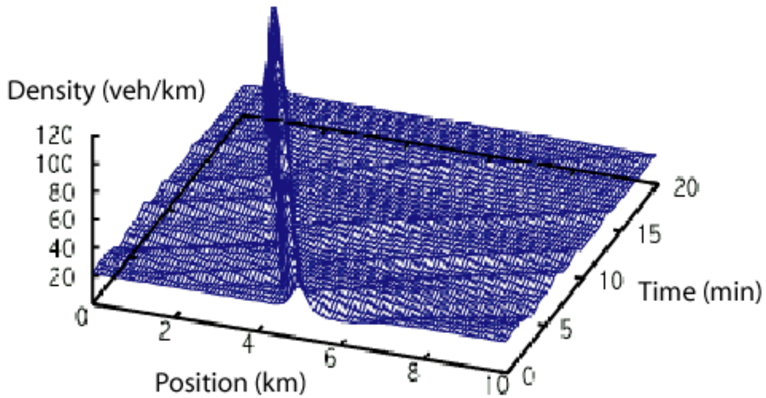


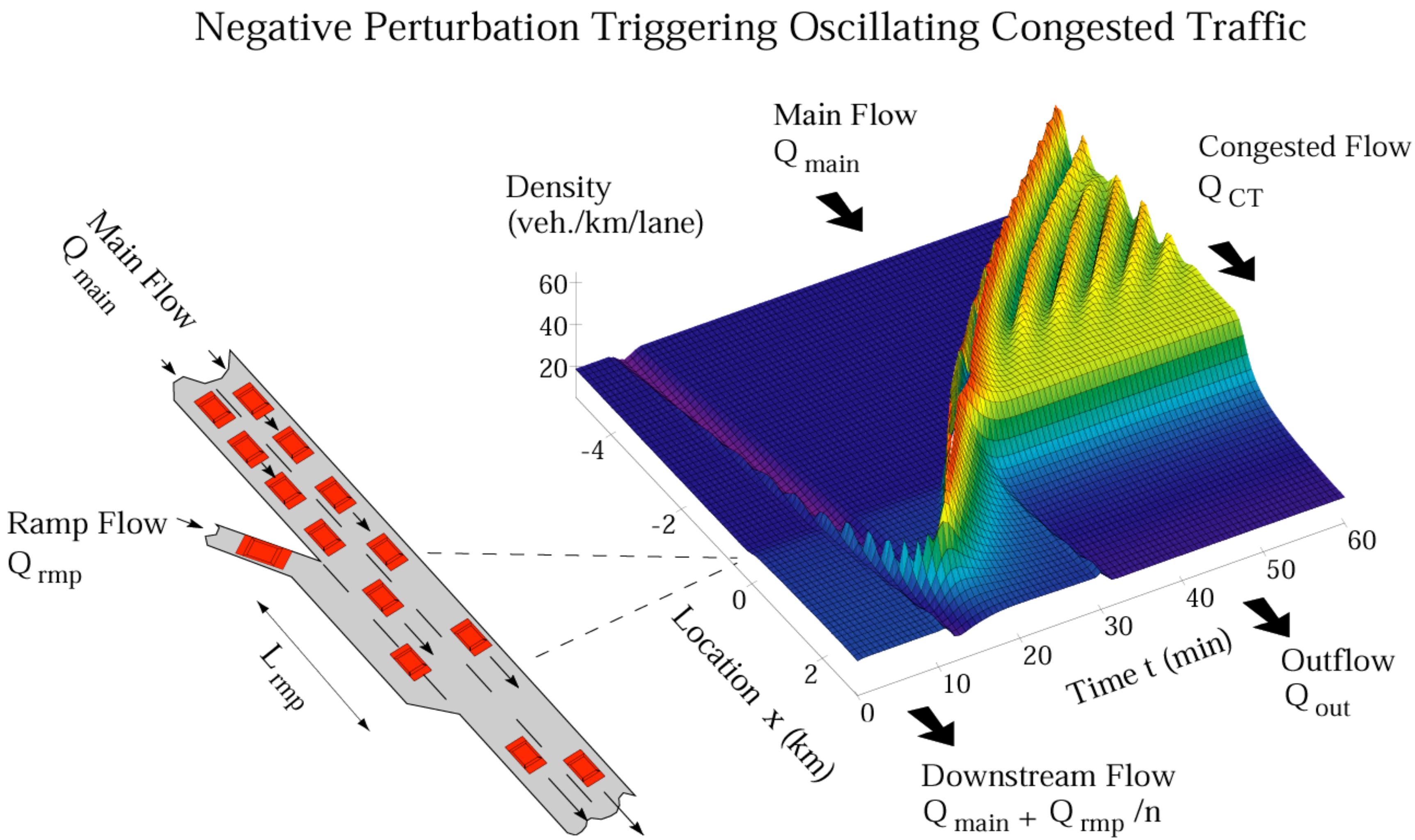

Decay of a Subcritical Perturbation

Growth of a Supercritical Perturbation

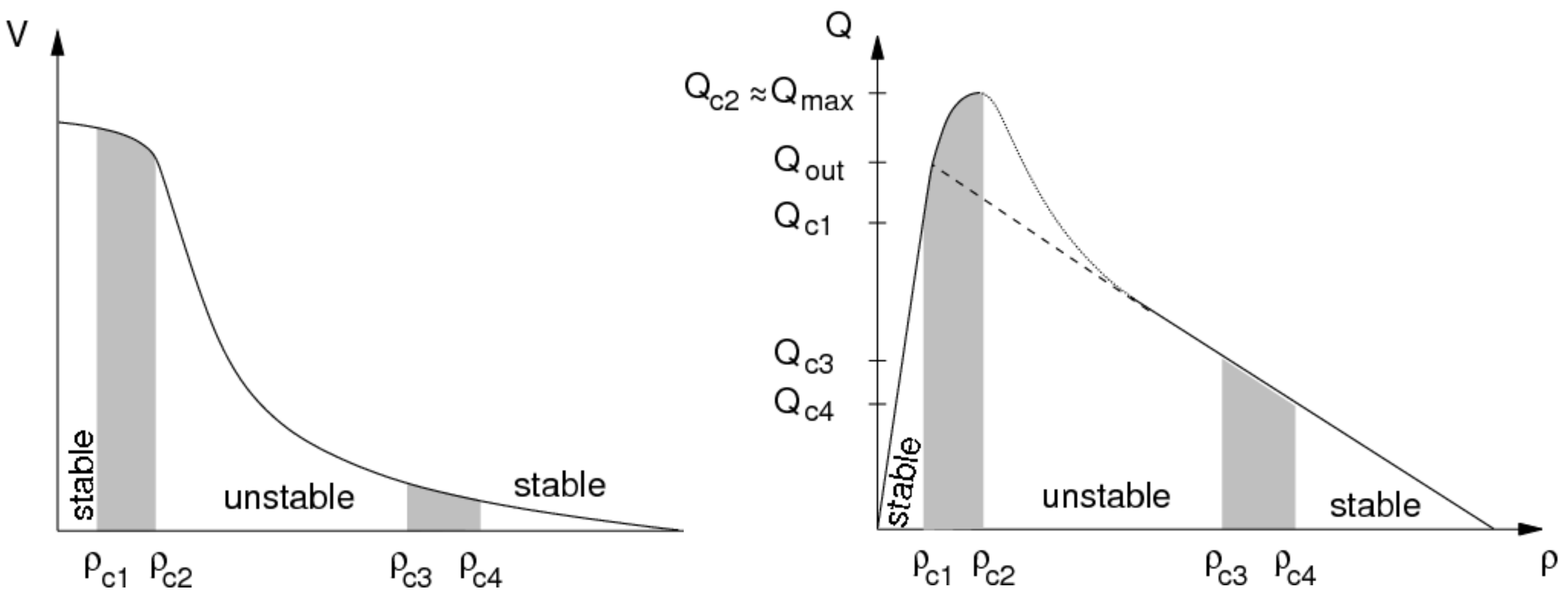


# Breakdown of Traffic due to a Supercritical Reduction of Traffic Flow



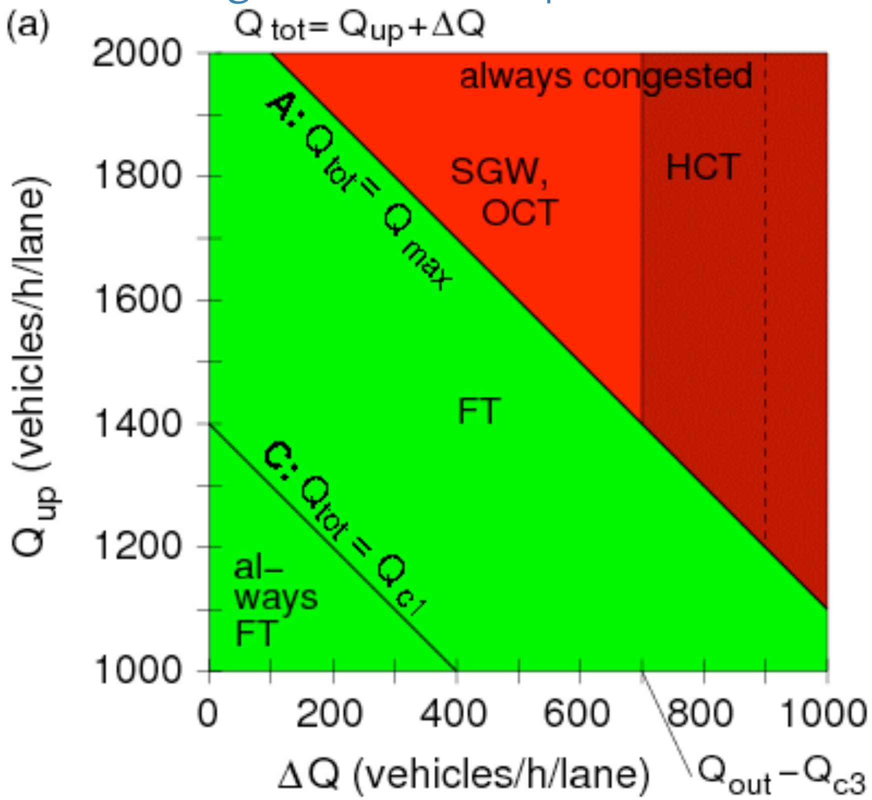
# Assumed Instability Diagram



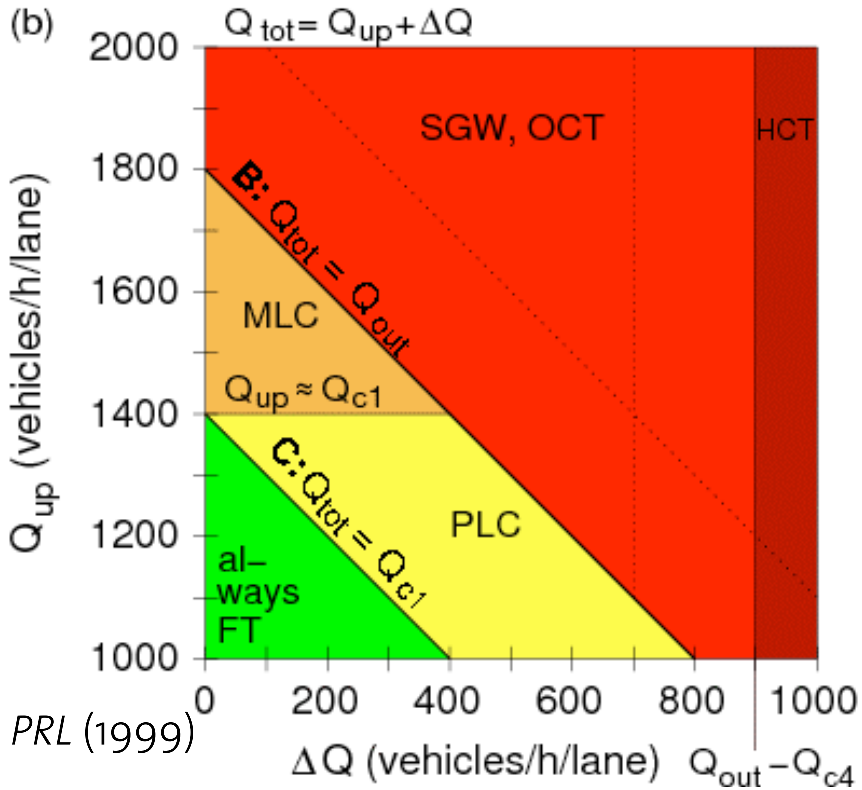

Grey areas = metastable regimes, where result depends on perturbation amplitude

# Phase Diagram of Traffic States and Universality Classes

Phase diagram for small perturbations




for large perturbations

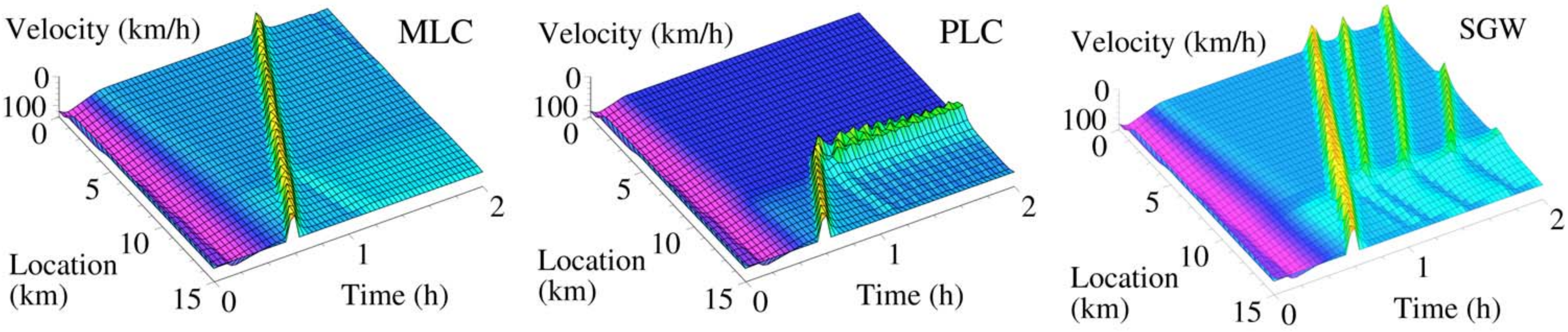


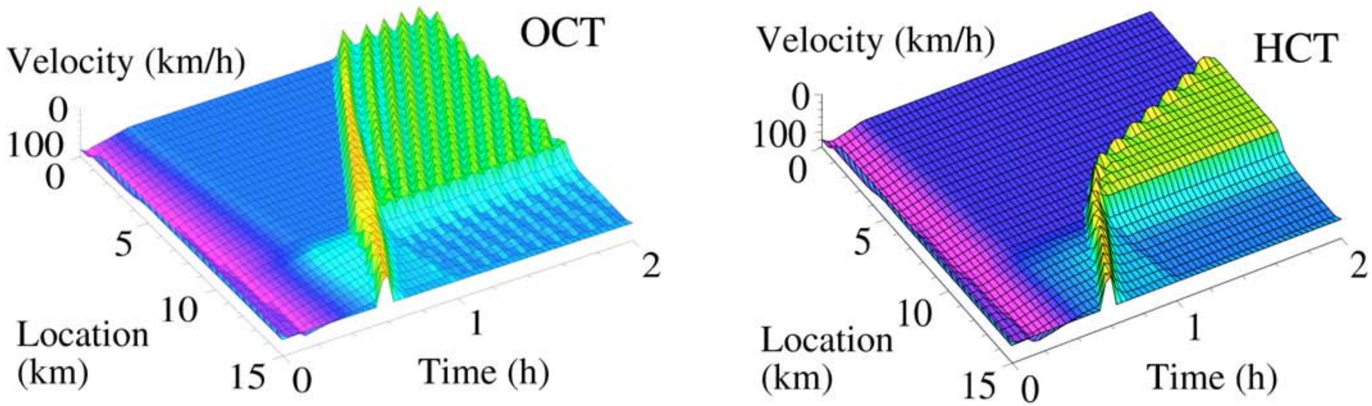

After: *PRL* (1999)

Phase diagrams are not only important to understand the conditions under which certain traffic states emerge. They also allow one to categorize the more than 100 traffic models into different universality classes. From the universality class that reproduces the empirically observed stylized facts, one may choose any representative, e.g. the simplest or the most accurate one, depending on the purpose.

# Congested Traffic States Simulated with a Macroscopic Traffic Model

Perturbing traffic flows and, paradoxically, even *decreasing* them may sometimes cause congestion.

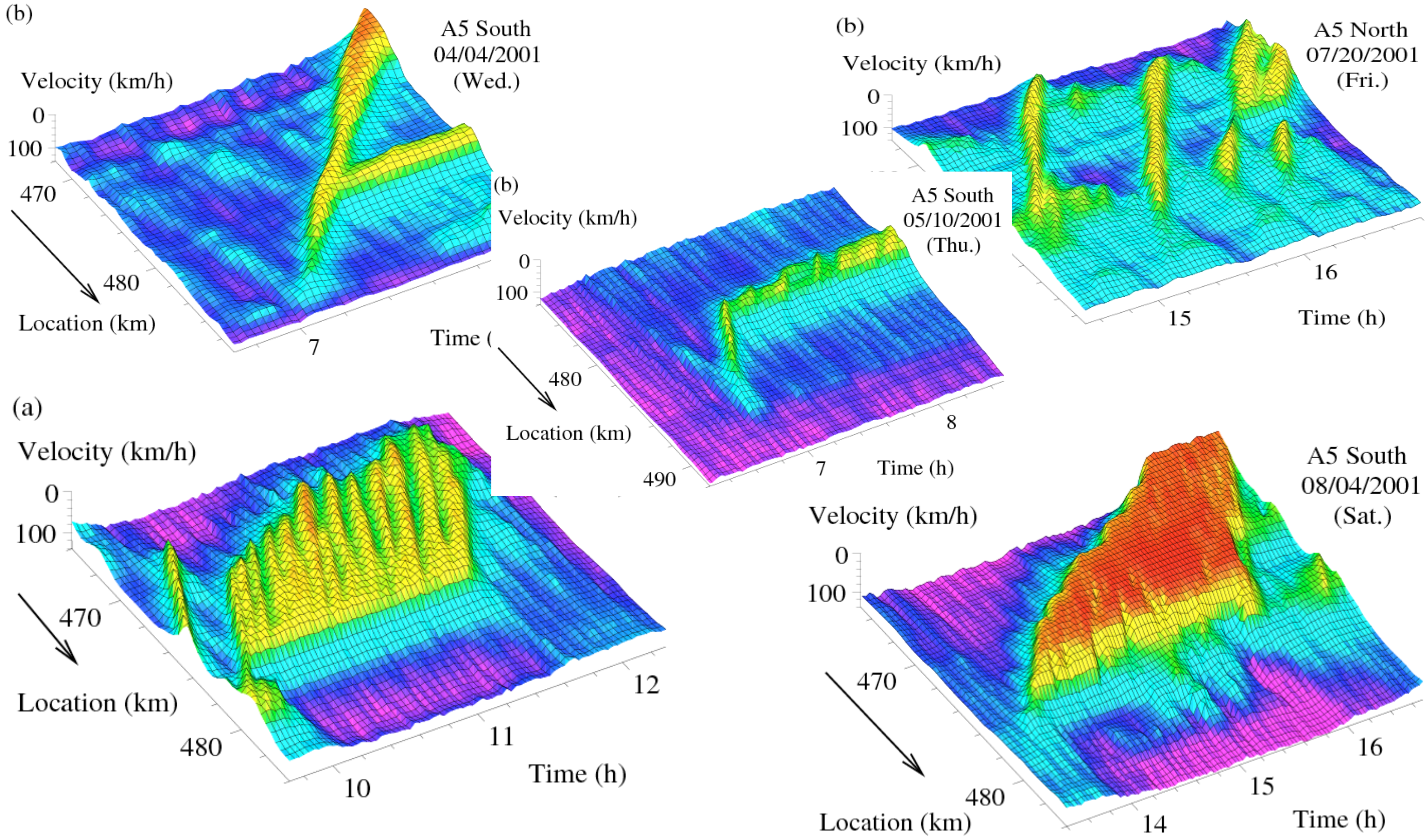


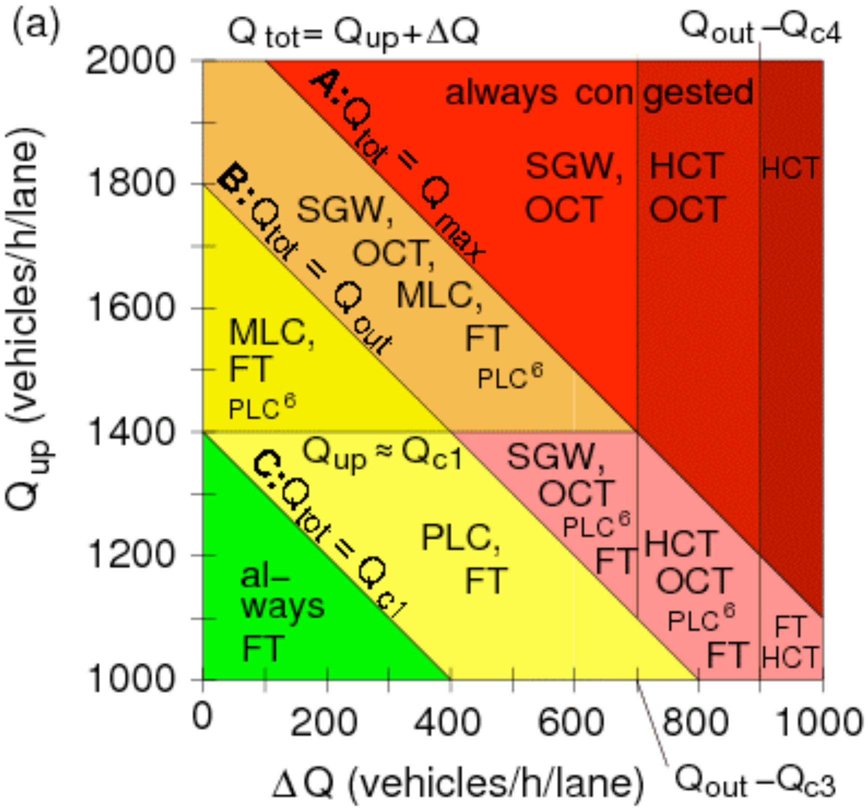

*Phys. Rev. Lett.* **82**, 4360 (1999).

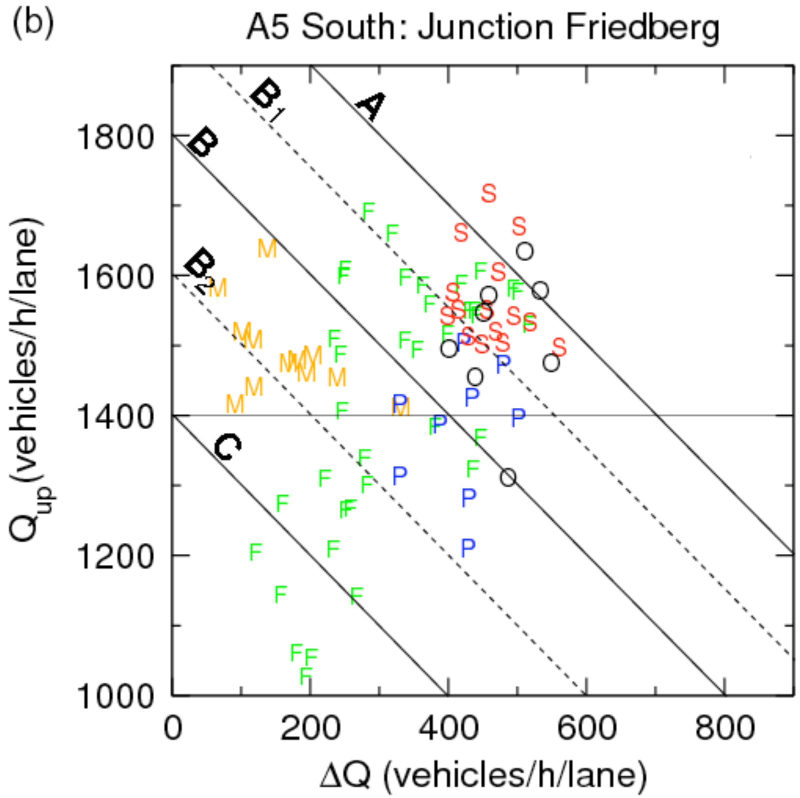
Similar congested traffic states are found for several other traffic models, including "microscopic" car-following models.

# Summary of Elementary Congestion Patterns



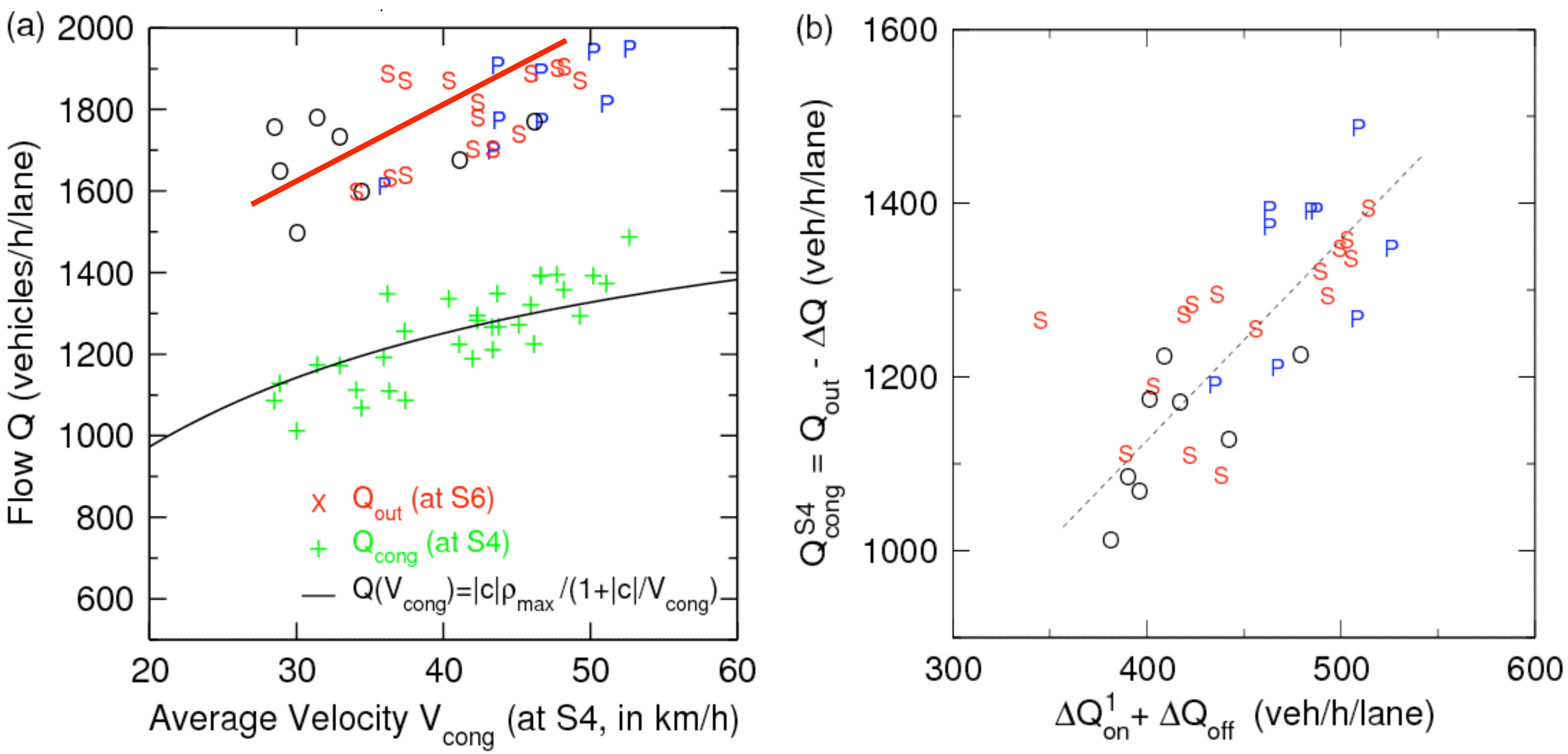
# Theoretical vs. Empirical Phase Diagram



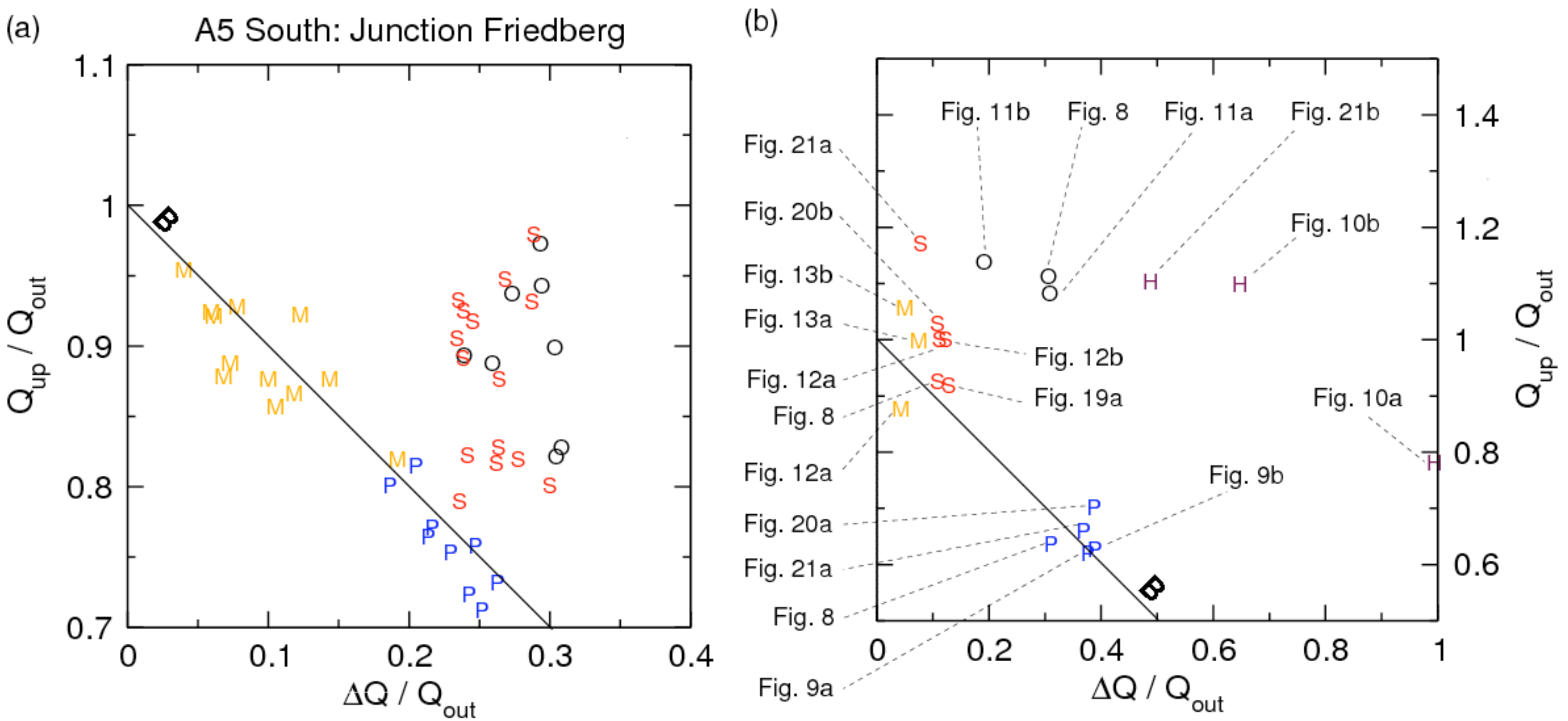

The outflow varies between B1 and B2. For statistical reasons?

# The Outflow Correlates with Other Traffic Variables



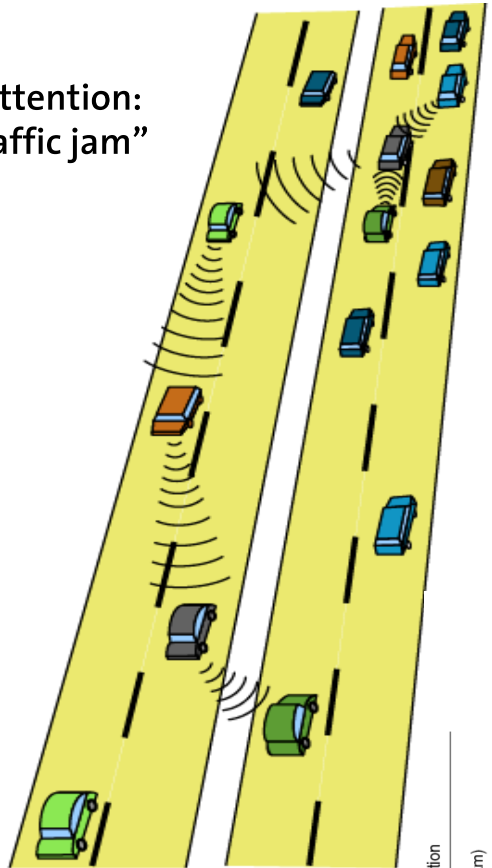
# Empirical Phase Diagram for Scaled Flows

A scaling by the outflow, that varies from day to day, gives a clearer picture.



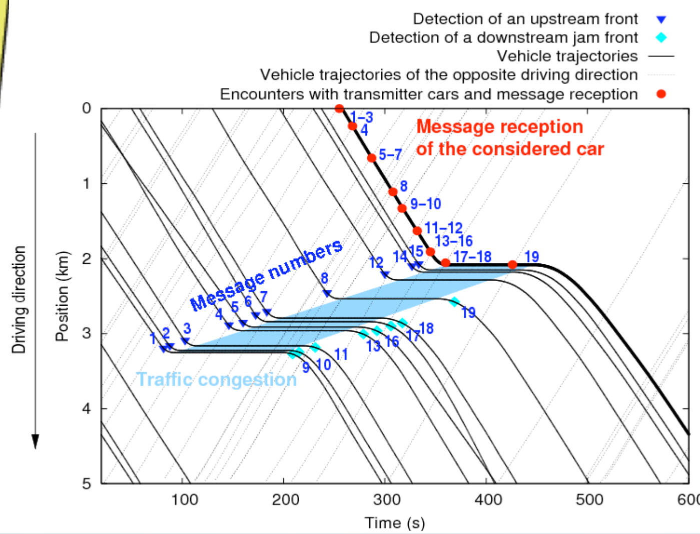
# Cooperative Driving Based on Autonomous Vehicle Interactions

**“Attention: Traffic jam”**



In: *Transportation Research Record* (2007)

- On-board data acquisition („perception“)
- Inter-vehicle communication
- Cooperative traffic state determination (“cognition”)
- Adaptive choice of driving strategy (“decision-making”)
- Driver information
- Traffic assistance (higher stability and capacity of traffic flow)


# Design of Traffic State Adaptive Cruise Control

Invent-VLA: Intelligent Adaptive Cruise Control (IACC) for the avoidance of traffic breakdowns and a faster recovery from congested traffic

**Free Traffic**
Normal driving mode

**Approaching Upstream End of Congestion**
Reduce desired deceleration for safety and convenience

### VLA Matrix for IDM

| aVLA/a | bVLA/b | Tvla/T |
|---|---|---|
| 1.0 | 1.0 | 1.0 |
| 1.0 | 0.7 | 1.0 |
| 1.0 | 1.0 | 1.0 |
| 1.0 | 1.0 | 0.7 |
| 2.0 | 1.0 | 0.5 |

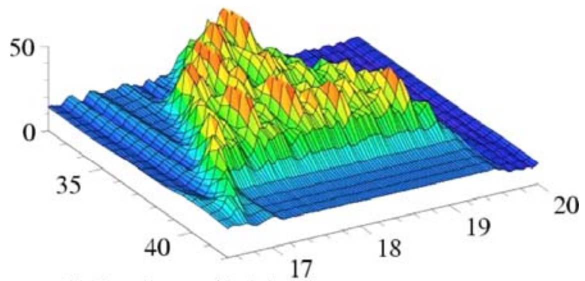
**Downstream Bottom of Congestion**
Forceful and accurately timed acceleration most important

**Driving in Congested Traffic (OCT/HCT)**
Normal driving mode
(or reduce oscillations)

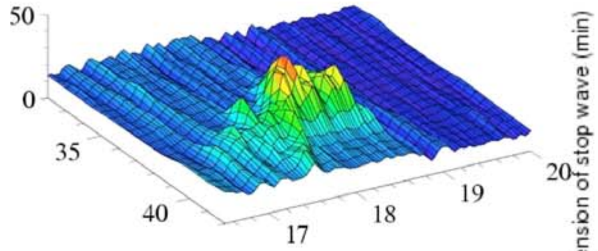
**Driving in Bottleneck Section**
Increase local capacity by decreasing time gaps
(dyn. homogenization)

# Enhancing Traffic Performance by Adaptive Cruise Control

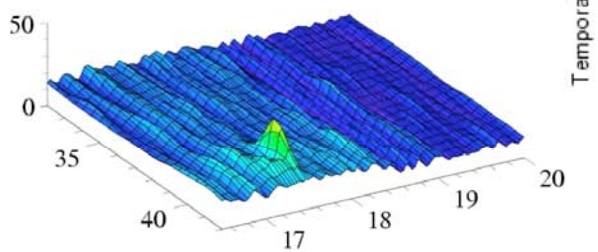
ρ(veh./km/lane)



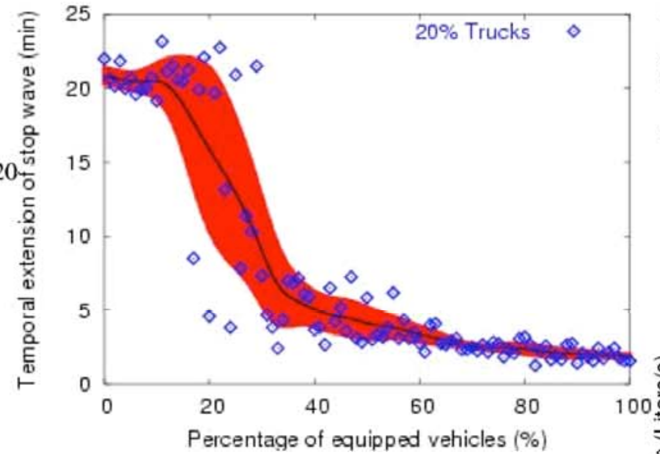

10% Equipped Vehicles

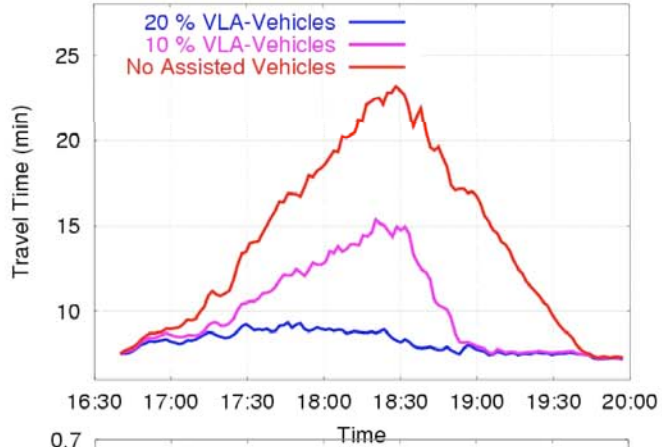


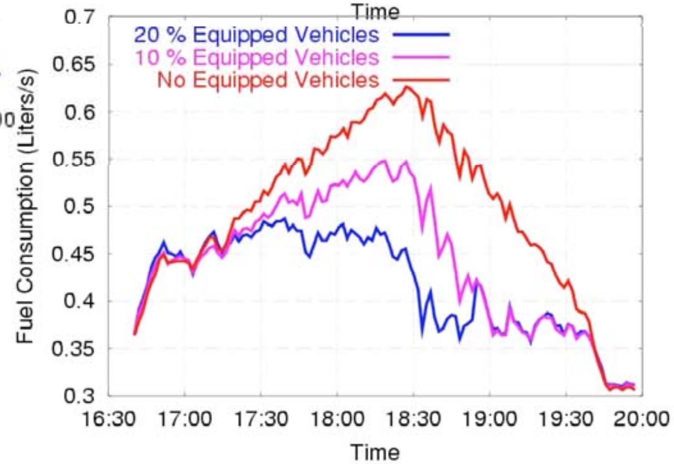

20% Equipped Vehicles




- Traffic breakdowns delayed
- Faster recovery to free traffic
- High impact on travel times
- Reduced fuel consumption and emissions



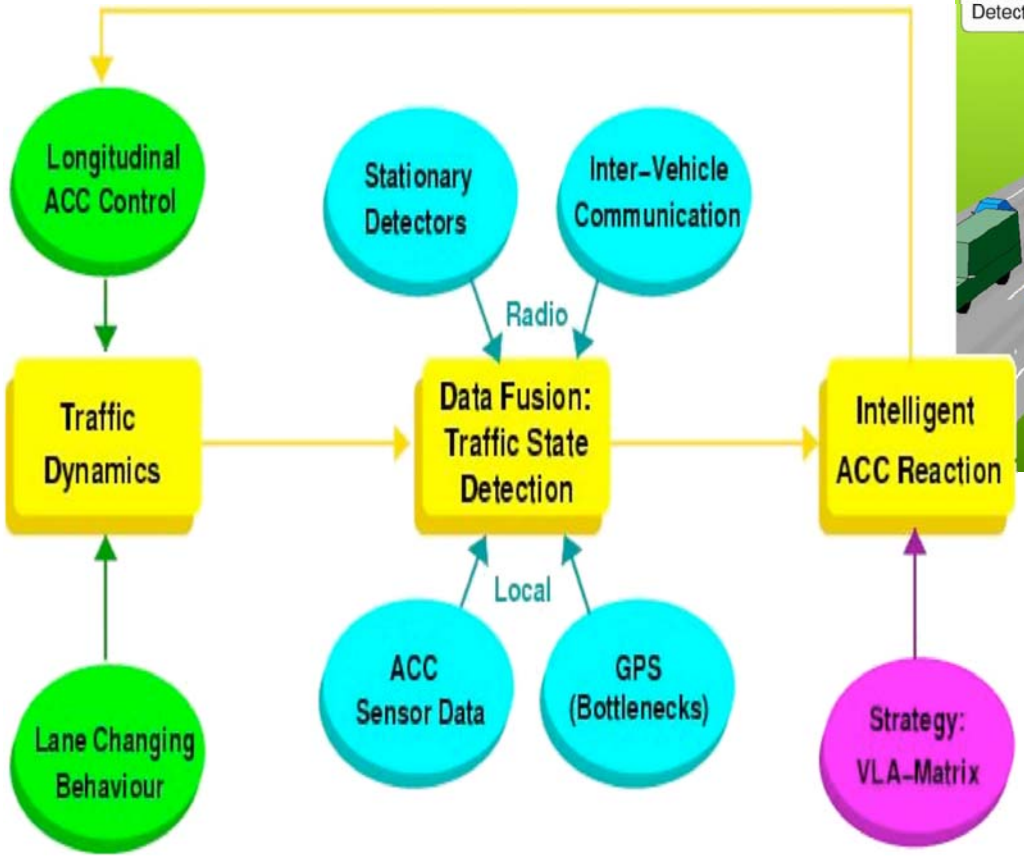



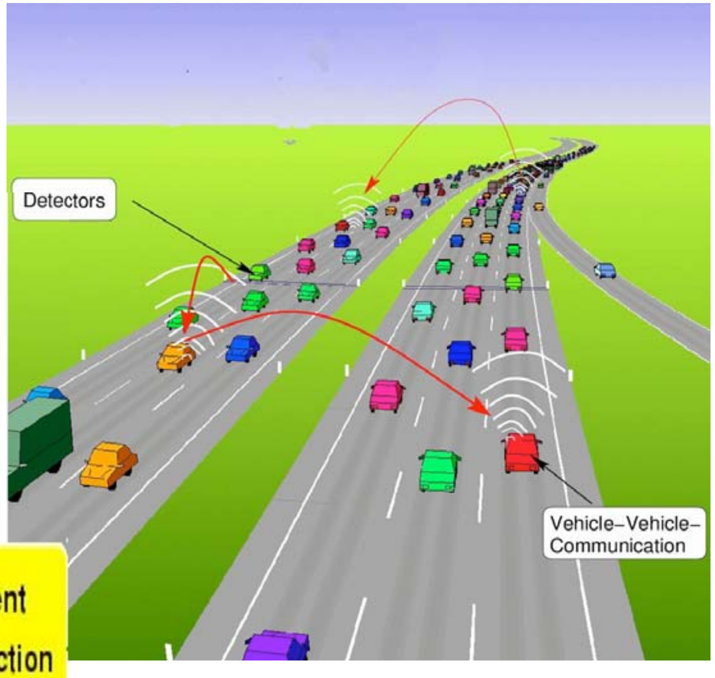




"Mechanism design",
in cooperation with

# 3D Assessment of Traffic Scenarios

# Data Fusion for Dynamic Traffic State Detection



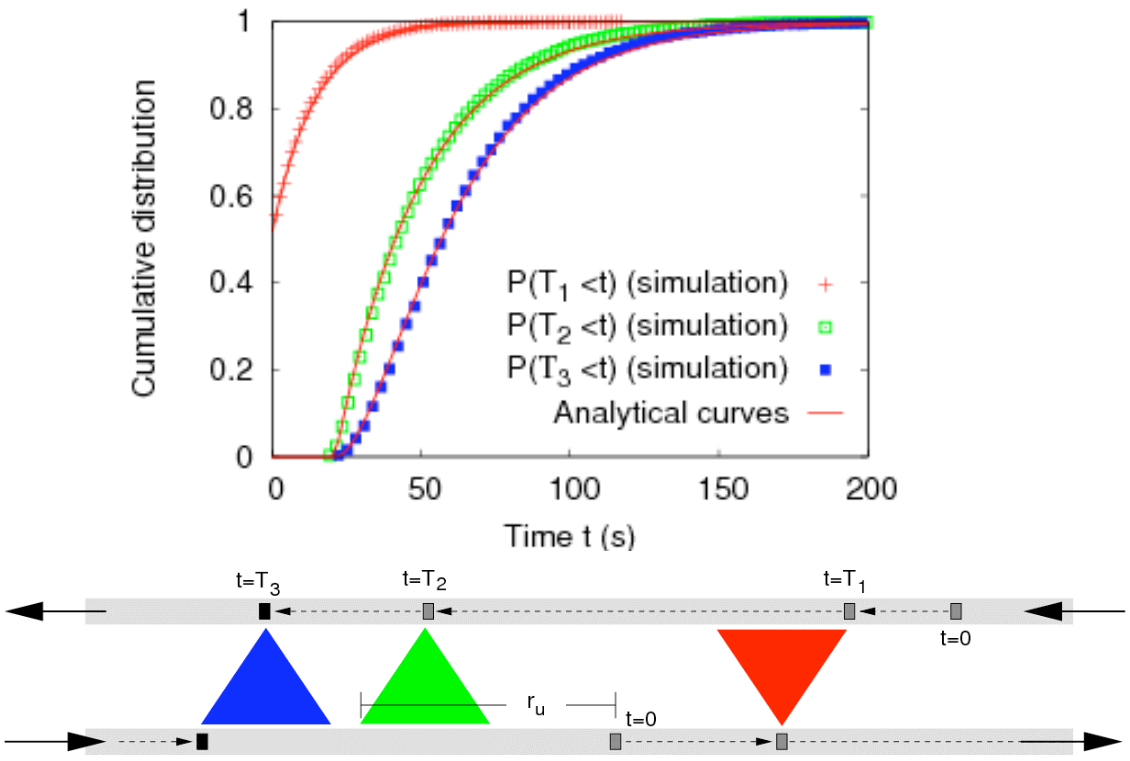



# Statistics of Message Transmission

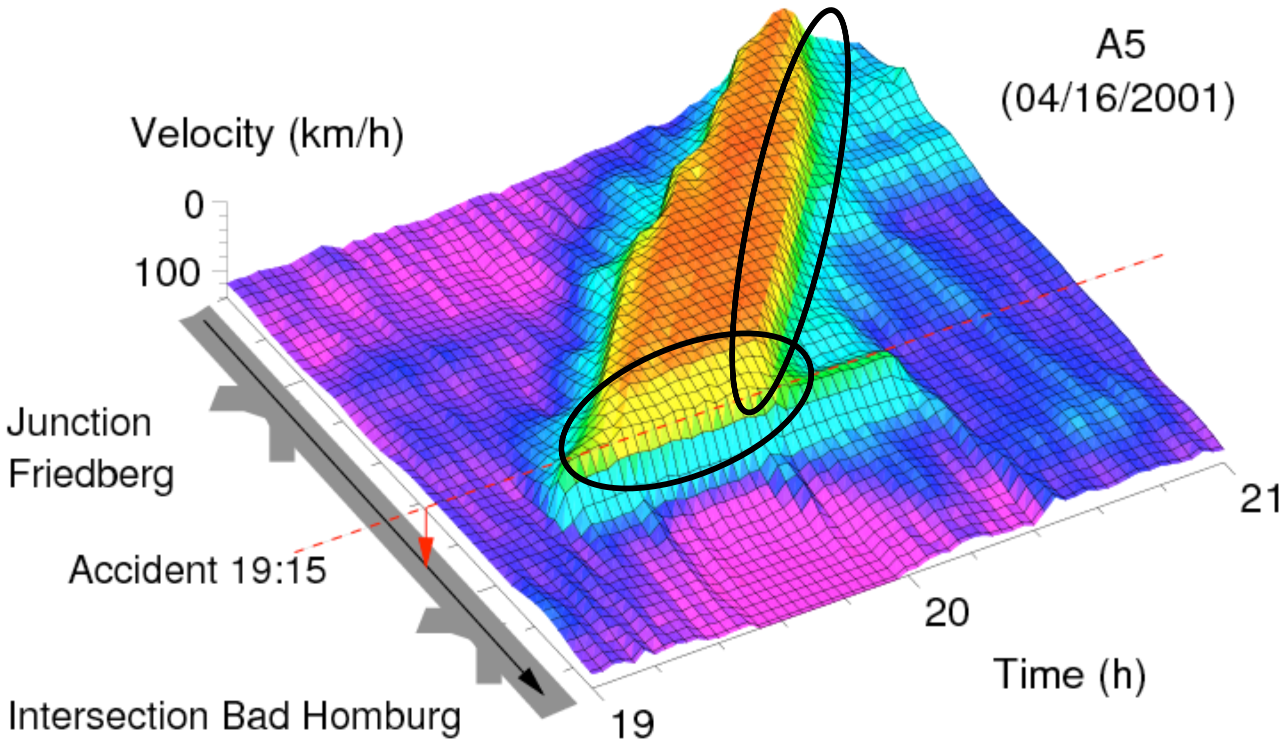
Distance between communicating vehicles exponentially distributed

→ Distributions for T1, T2, and T3,

e.g. $$P(T_2 < t) = \Theta\left(t - \frac{r_{\rm up} - 2r}{v}\right)\left(1 - e^{-\beta(2r + vt - r_{\rm up})}\right)$$

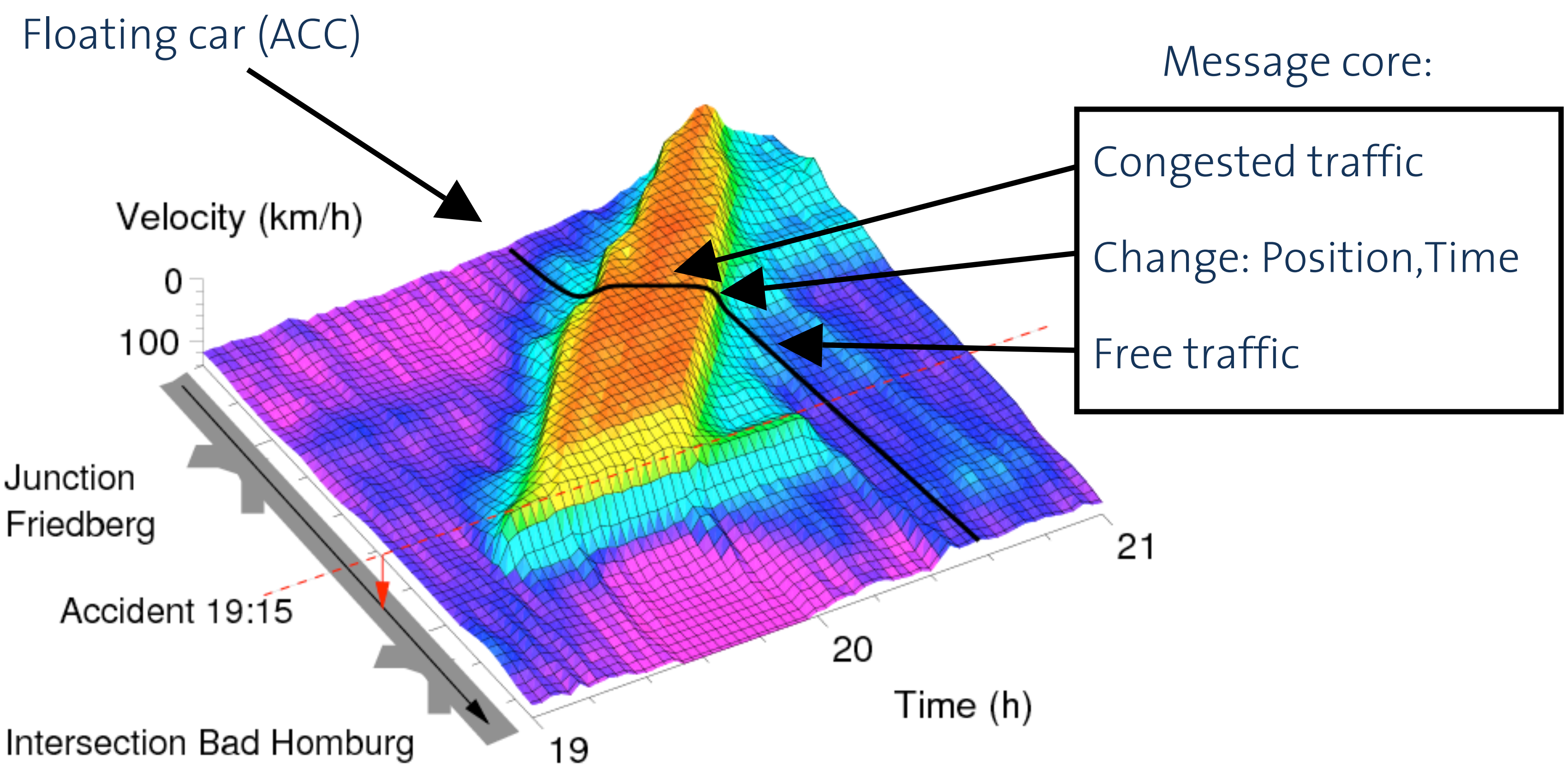


# Spatiotemporal Dynamics of a Traffic Jam

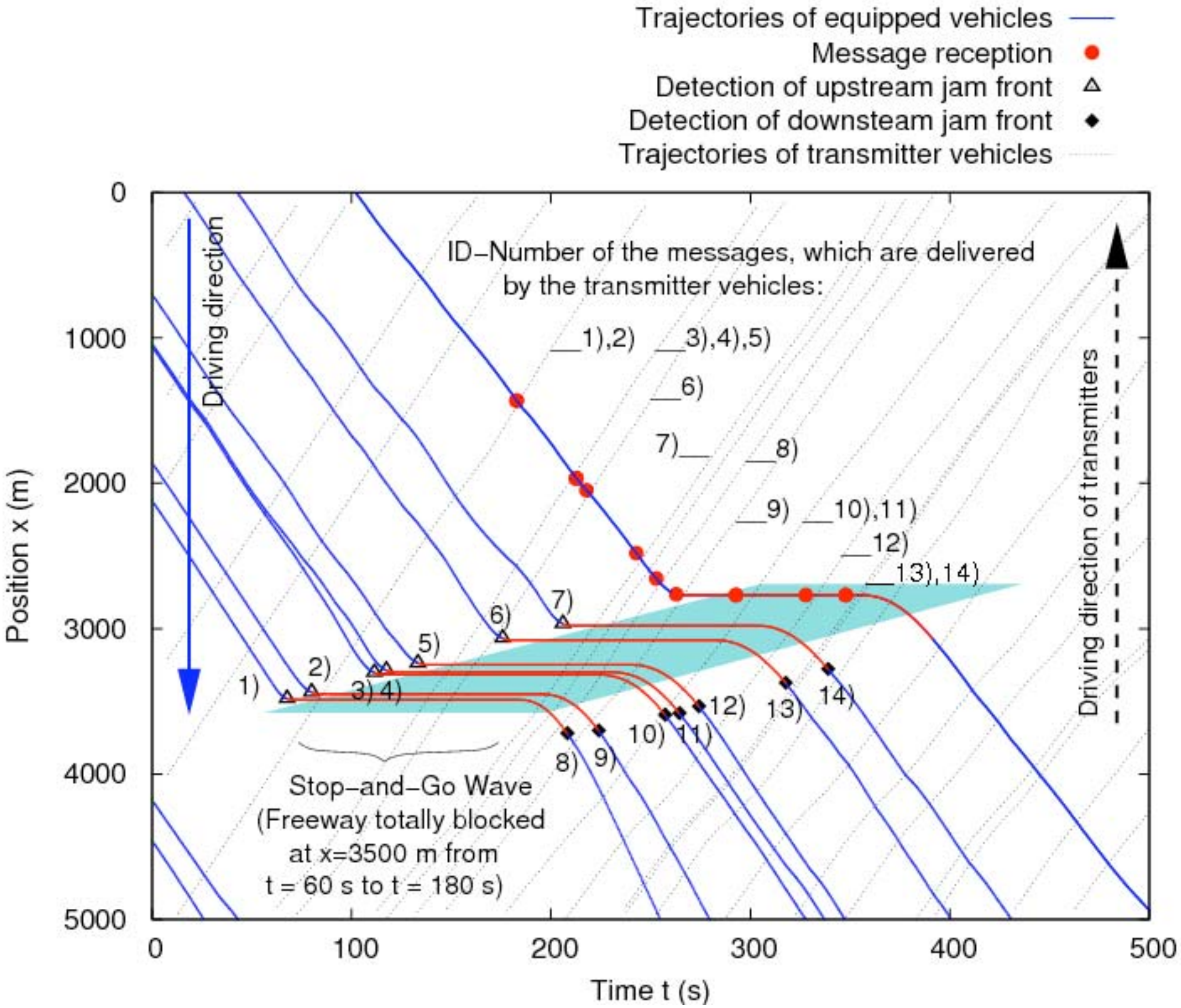



Downstream jam fronts

# Jam Front Detection - Message Generation

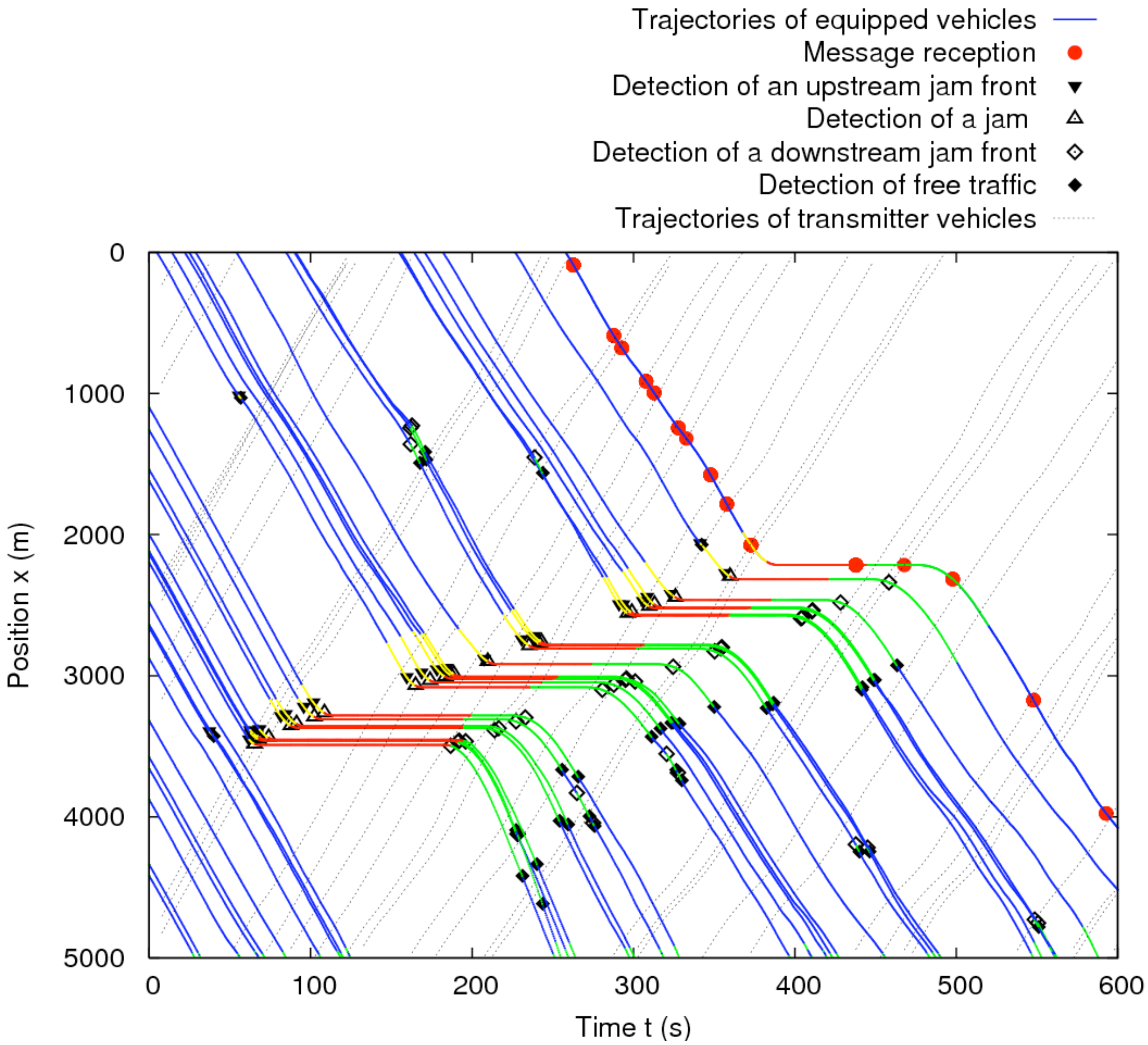


# Example: Information about a Stop-and-Go Wave




1) Upstream jam front at x=3481 m, t=68 s
2) Upstream jam front at x=3436 m, t=80 s
3) Upstream jam front at x=3302 m, t=111 s
4) Upstream jam front at x=3285 m, t=117 s
5) Upstream jam front at x=3236 m, t=133 s
6) Upstream jam front at x=3065 m, t=176 s
7) Upstream jam front at x=2966 m, t=206 s
8) Free traffic at x=3719 m, t=208 s
9) ...

# Traffic-Adaptive Driving Strategy for ACC



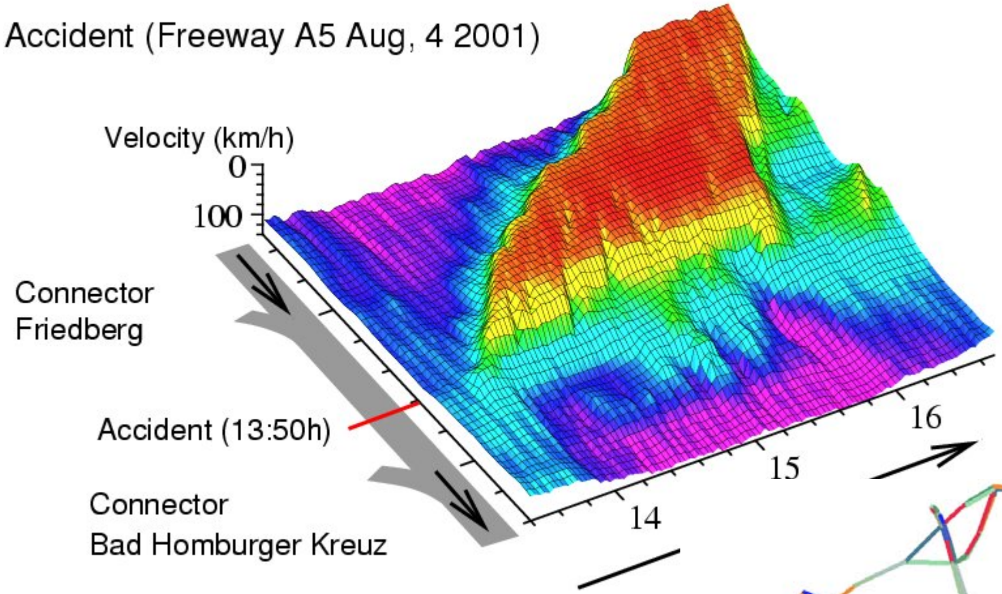

Color of trajectories

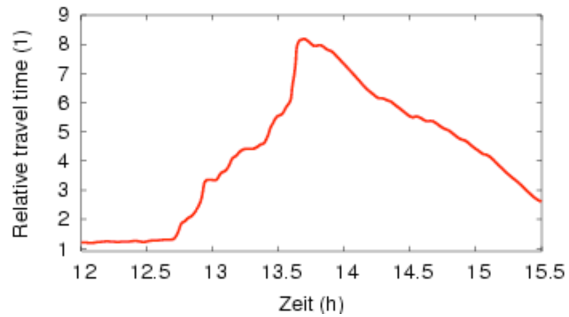
≡

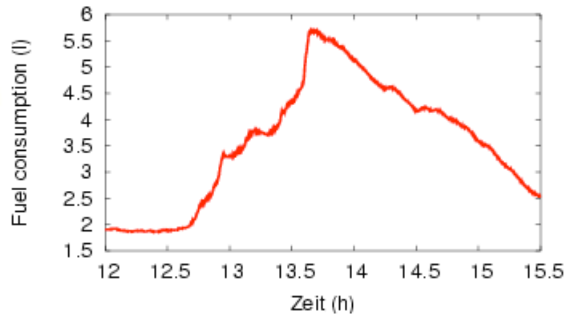
ACC operating state:

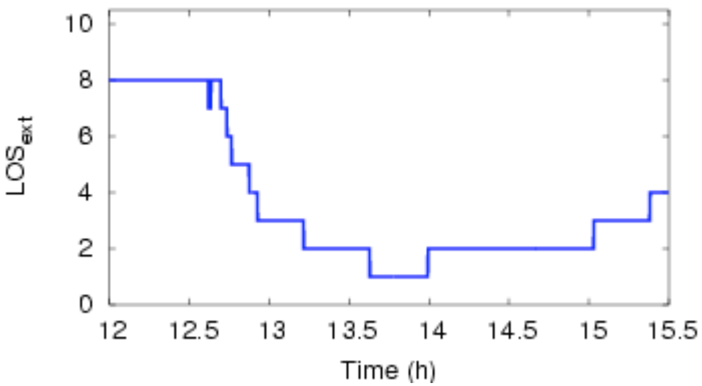
- Free traffic
- Approaching to jam
- Jam
- Downstream jam front

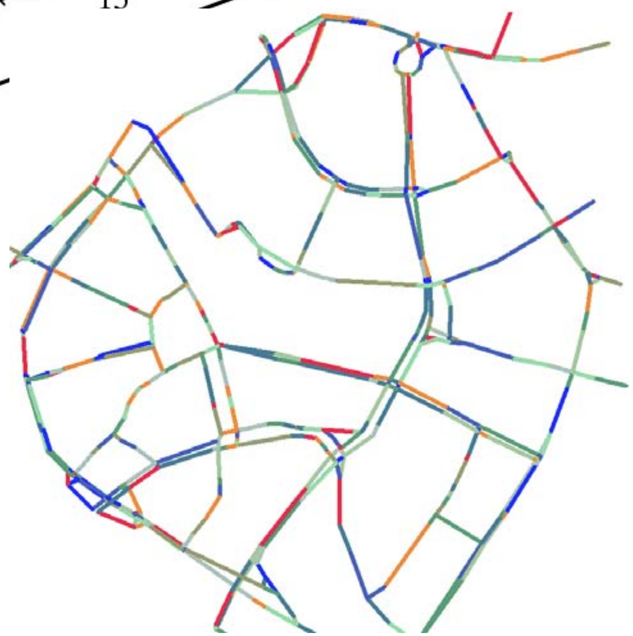
# Evaluation of a Driver-Oriented Level of Service

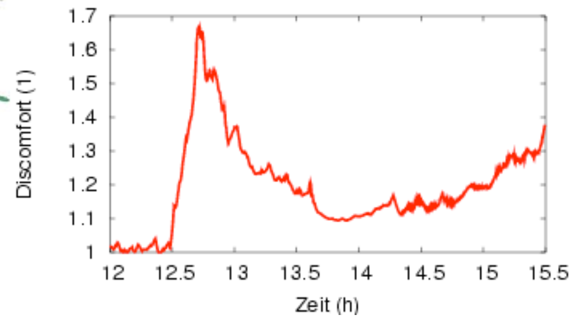


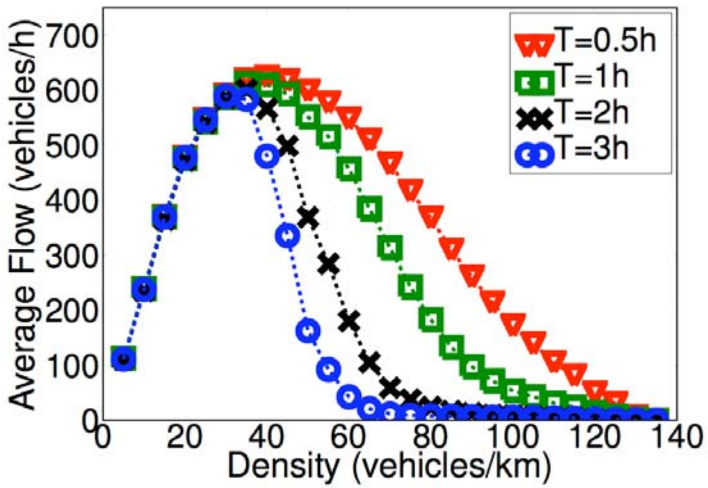



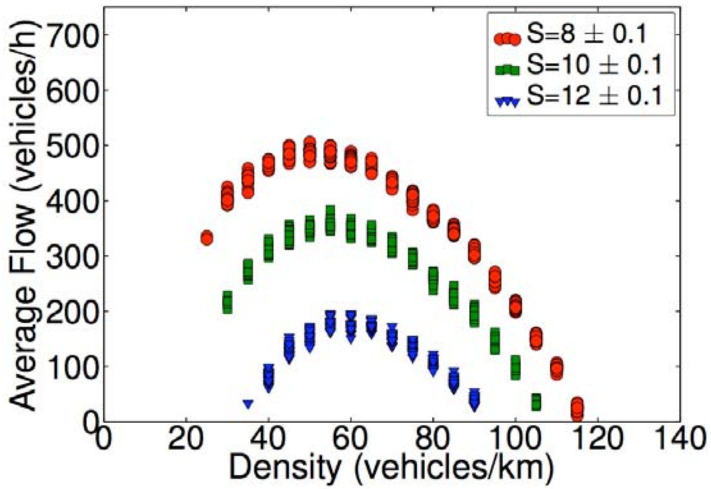



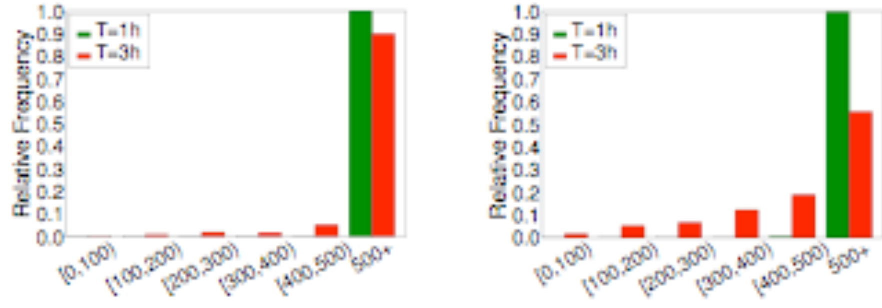





# Variability of Urban Traffic Flows

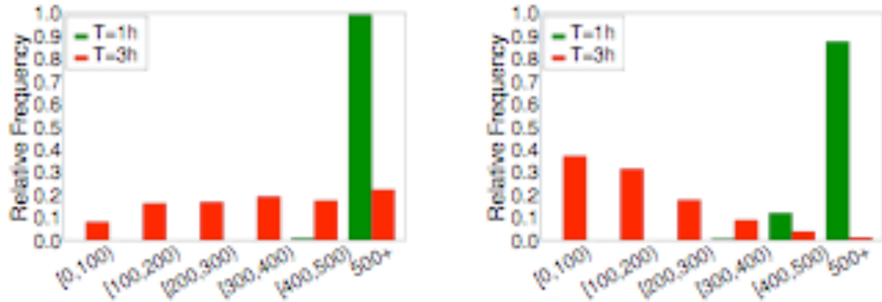


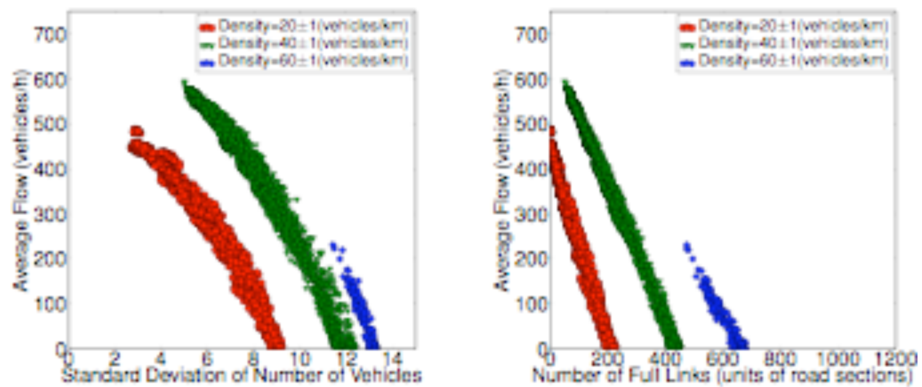




(a) Density=35 vehicles/km

(b) Density=40 vehicles/km



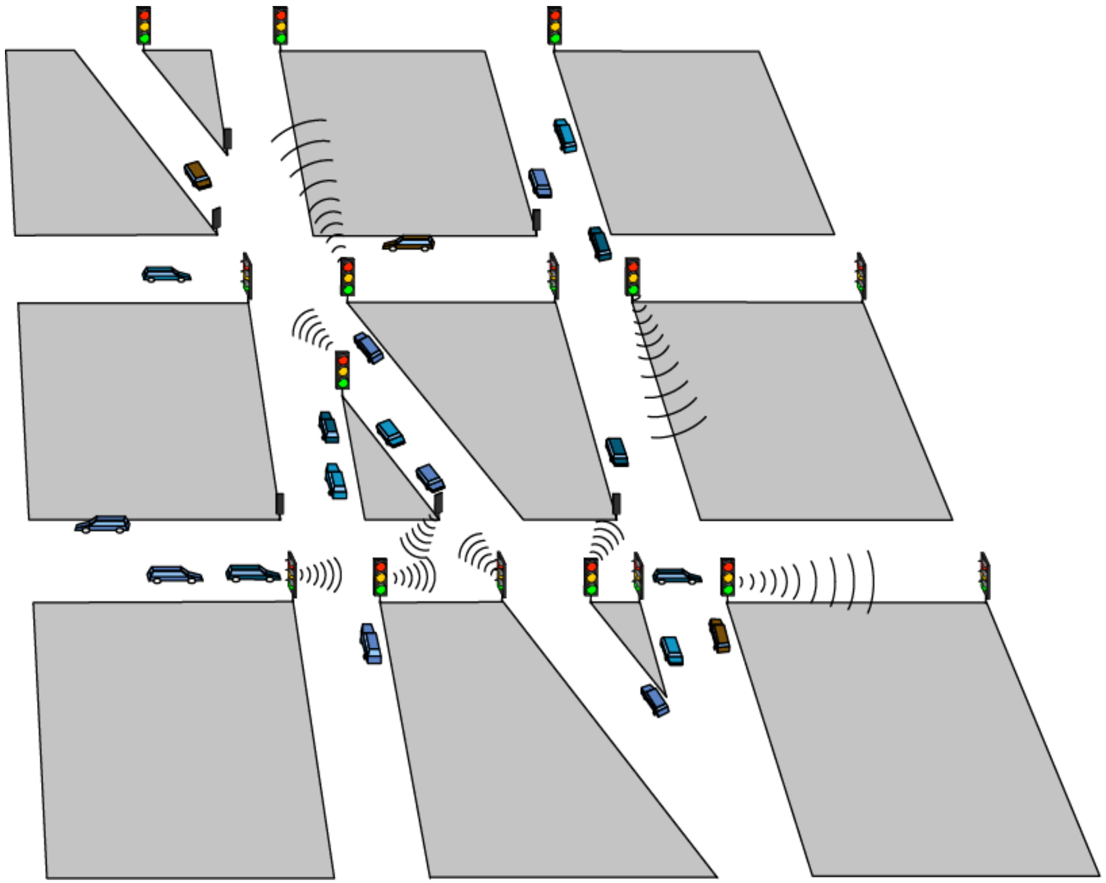




(a)

(b)

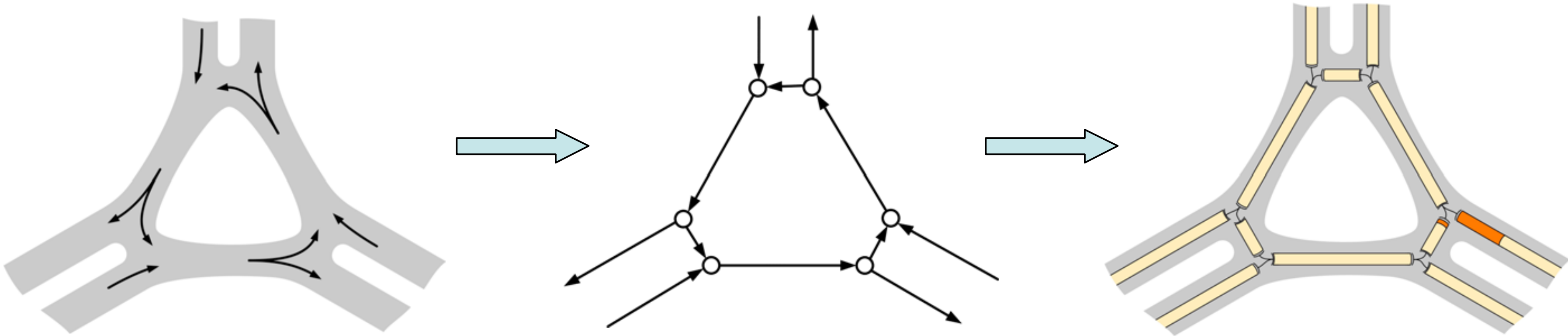
# Adaptive Traffic Light Control

- 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**

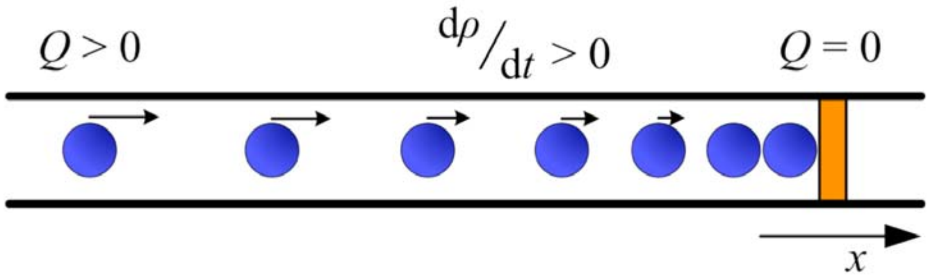
# Traffic Dynamics: Macroscopic Approach

- "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:

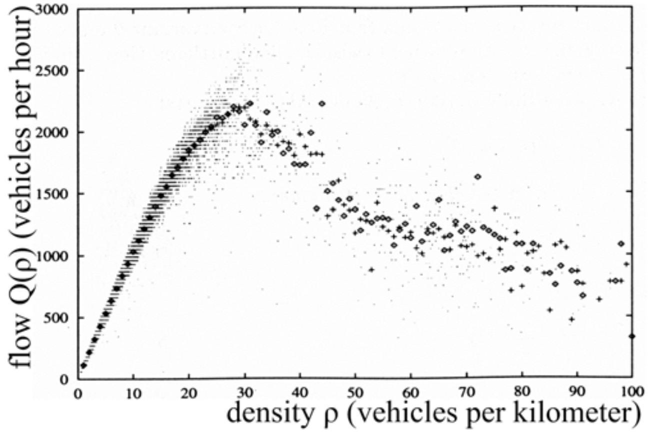
$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial Q(x,t)}{\partial x} = 0$$

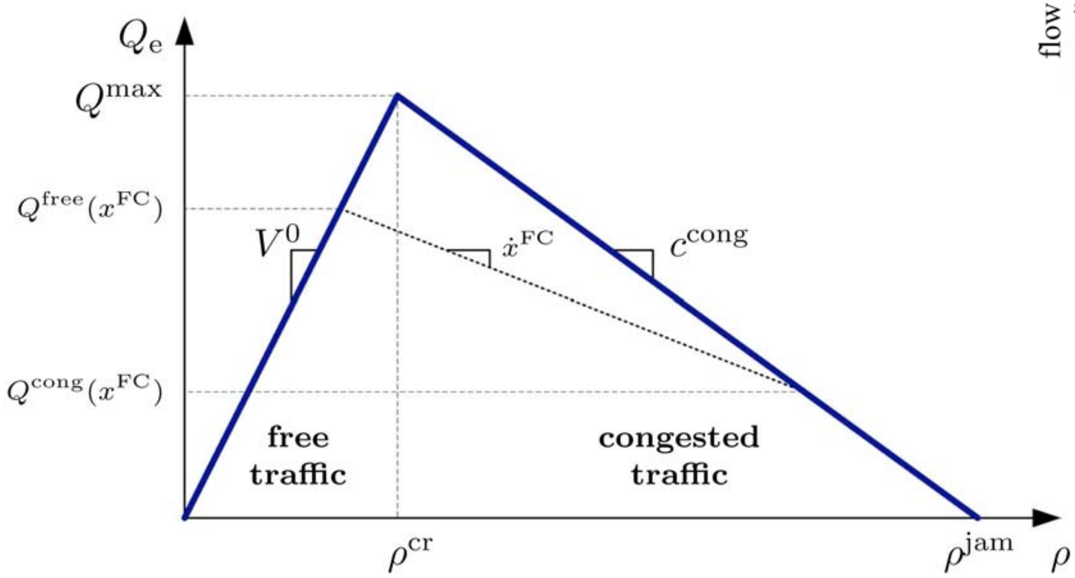


# Traffic Dynamics: Fundamental Diagram

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

(Helbing 1997)




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

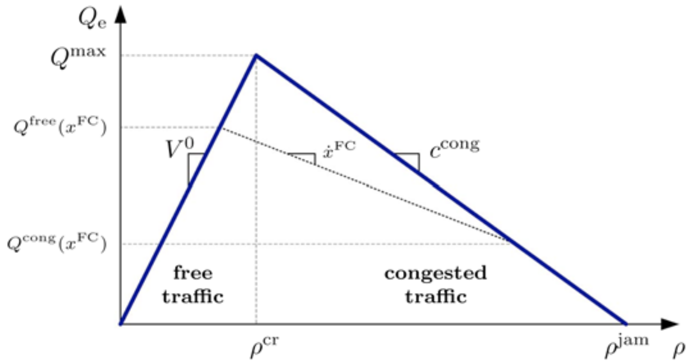
Derivation $Q_e$' plays important role!

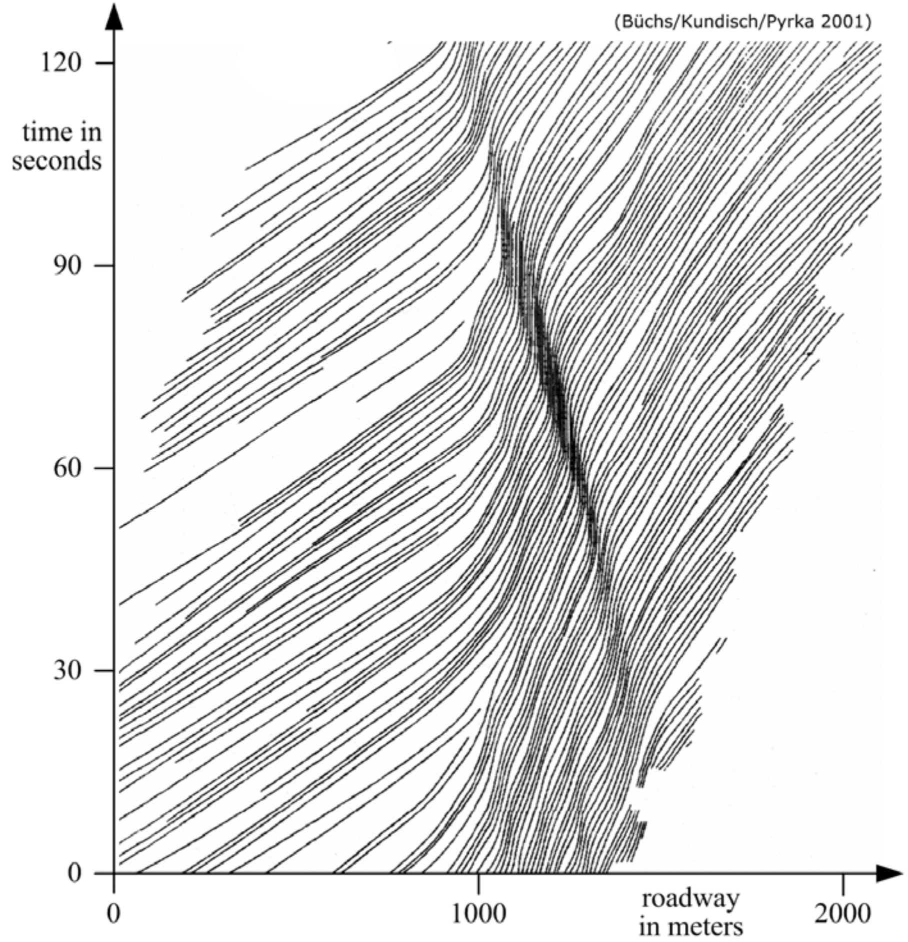
# Traffic Dynamics: Shock Waves

- Propagation velocity *c(ρ)*

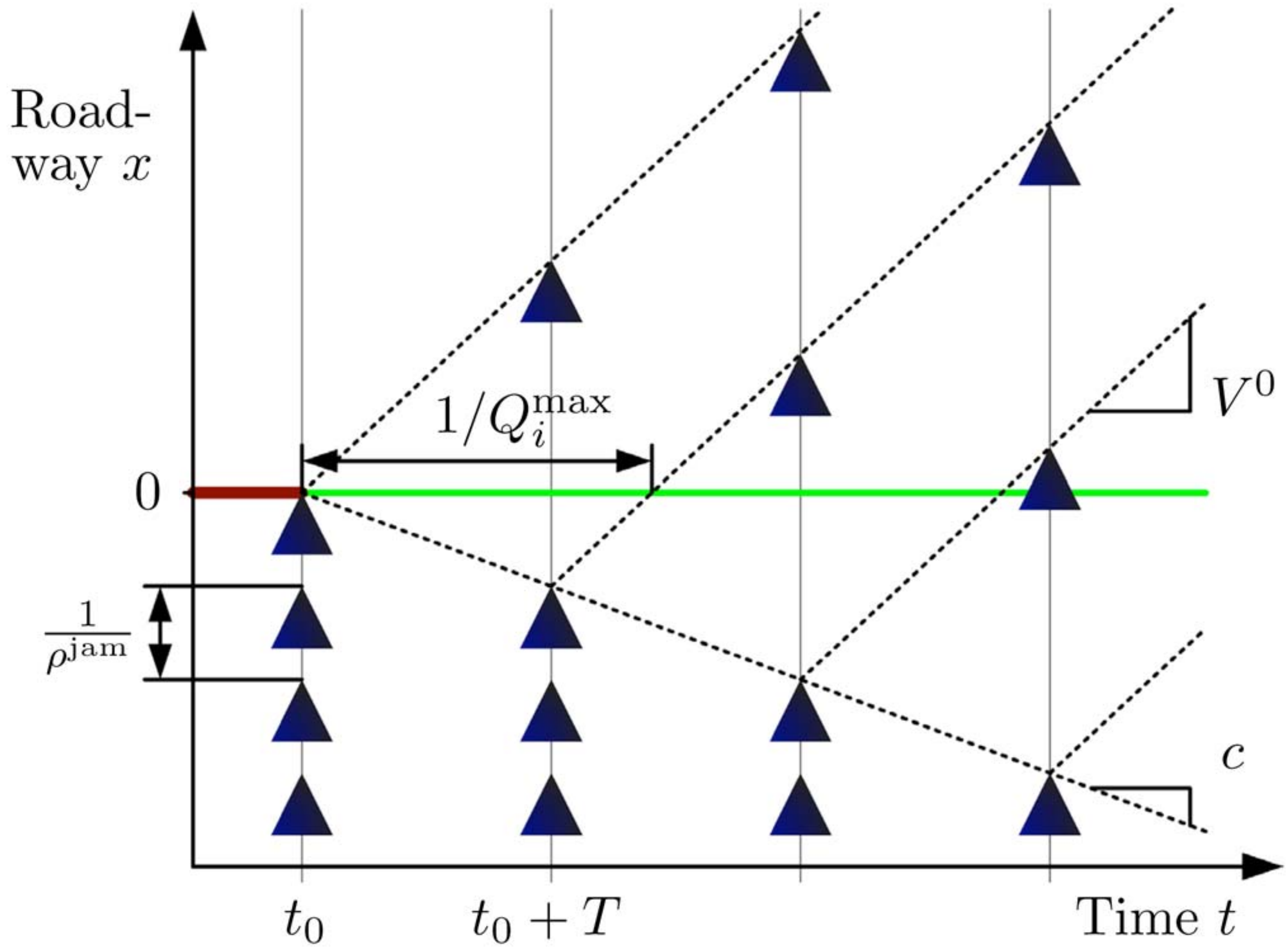
$$c(\rho) = \frac{\mathrm{d}Q_e(\rho)}{\mathrm{d}\rho}$$

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



# 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

$\rho_{\text{jam}}$ = jam density

The number $N_i$ of vehicles in section $i$ changes according to

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

$Q_i^{\text{arr}}$ = arrival rate of vehicles

$Q_i^{\text{dep}}$ = 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

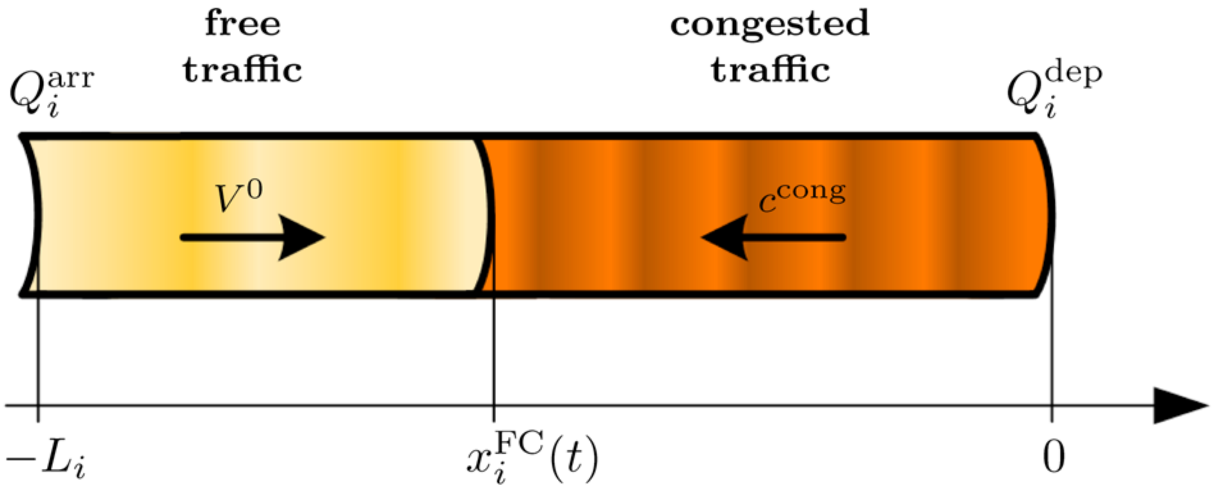
$$\rho_i^{\text{free}}(Q_i) = Q_i / V_i^0,$$

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

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

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

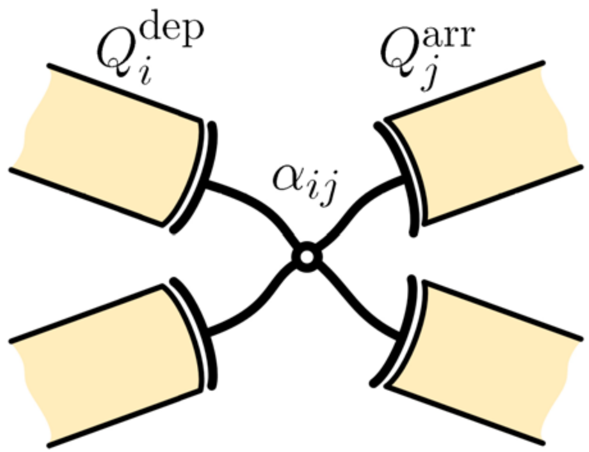
# Network Links: Homogenous Road Sections



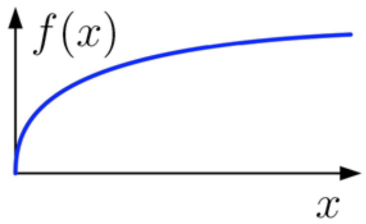

- Movement of congestion
$$\frac{\mathrm{d}}{\mathrm{d}t} x_i^{\mathrm{FC}} = \frac{\Delta Q\left(x_i^{\mathrm{FC}}\right)}{\Delta \rho\left(x_i^{\mathrm{FC}}\right)}$$
- Number of vehicles
$$\frac{\mathrm{d}}{\mathrm{d}t} N_i(t) = Q_i^{\mathrm{arr}}(t) - Q_i^{\mathrm{dep}}(t)$$
- Travel time
$$\frac{\mathrm{d}}{\mathrm{d}t}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

# Network Nodes: Connectors

- Side Conditions
  - Conservation $$\sum_i Q_i^{\text{dep}} = \sum_j Q_j^{\text{arr}}$$
  - Non-negativity $$Q_i^{\text{dep}} \geq 0$$ $$Q_j^{\text{arr}} \geq 0$$
  - Upper boundary $$Q_i^{\text{dep}} \leq Q_i^{\text{dep,pot}}$$ $$Q_j^{\text{arr}} \leq Q_j^{\text{arr,pot}}$$
  - Branching $$\sum_i \alpha_{ij} Q_i^{\text{dep}} = Q_j^{\text{arr}}$$

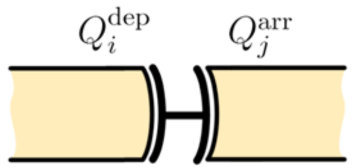



- Goal function $$F = \sum_i f(Q_i^{\text{dep}}) \rightarrow \max$$ $$f(x) = x^p \quad \text{with } p \ll 1$$

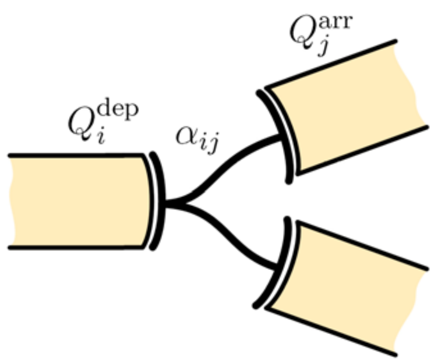


# Network Nodes: Special Cases

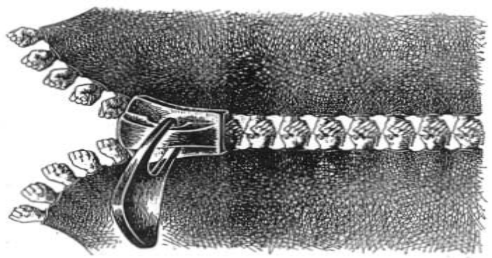
- **1 to 1:** $$Q_i^{\mathrm{dep}} = Q_j^{\mathrm{arr}} = \min\left\{Q_i^{\mathrm{dep,pot}}, Q_j^{\mathrm{arr,pot}}\right\}$$

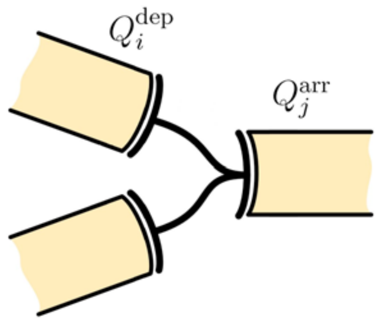



- **1 to n:** Diverging $$Q_i^{\mathrm{dep}} = \min\left\{Q_i^{\mathrm{dep,pot}}, \min_j \frac{Q_j^{\mathrm{arr,pot}}}{\alpha_{ij}}\right\}$$
$$Q_j^{\mathrm{arr}} = \alpha_{ij} Q_i^{\mathrm{dep}}$$

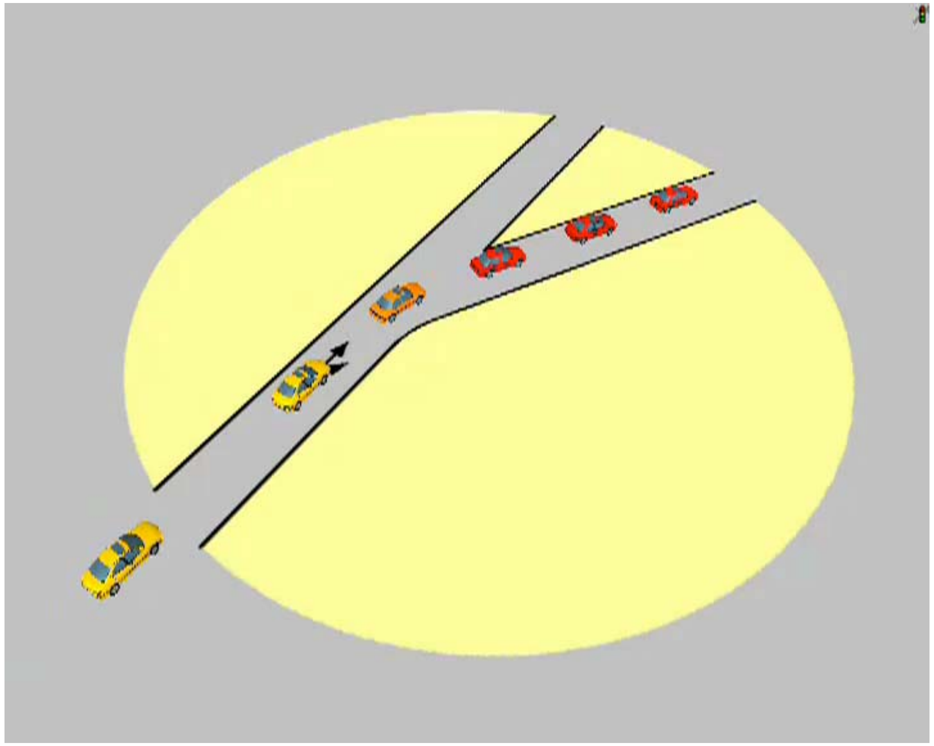


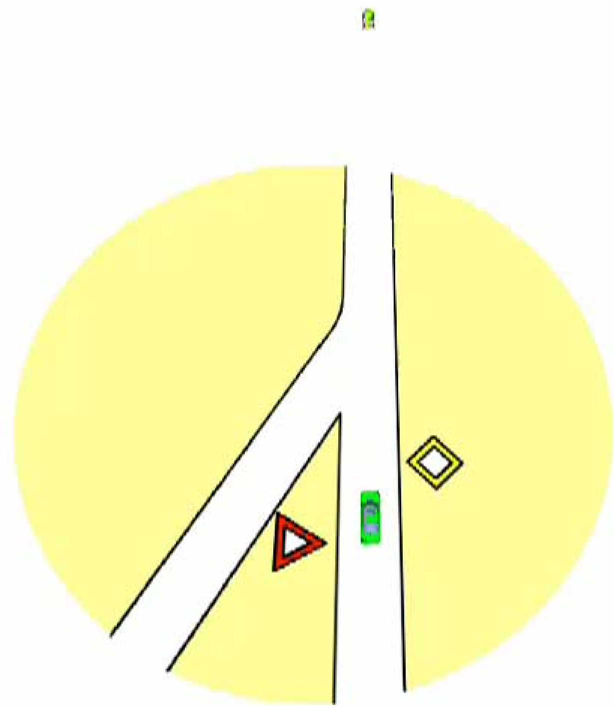

- **n to 1:** Merging





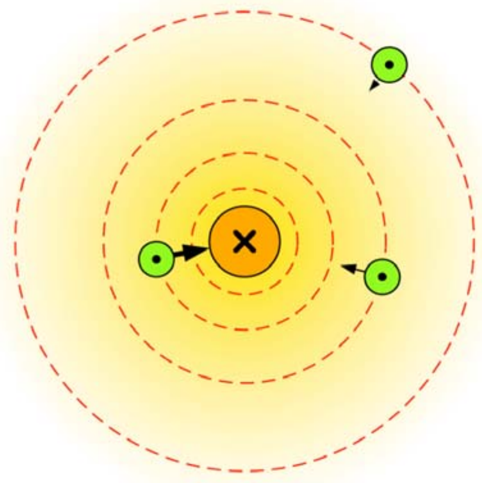
# Simulation of Diverges and Merges



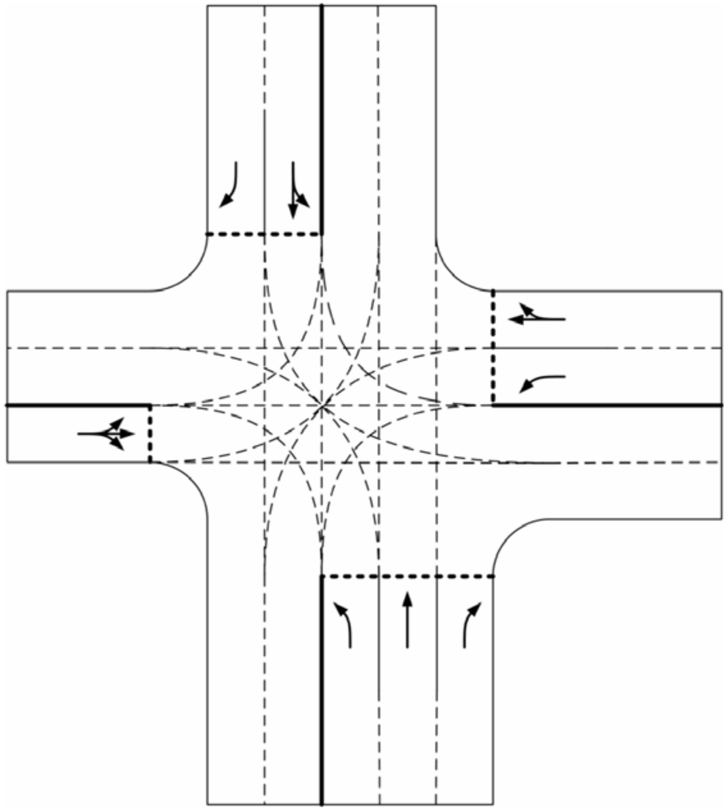


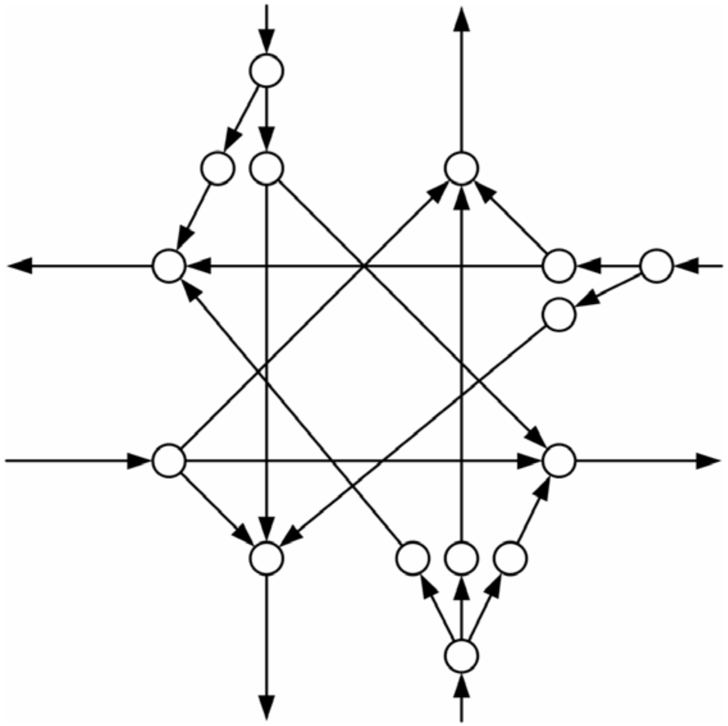
# Attractiveness of Sinks

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



# Network Representation of Intersections

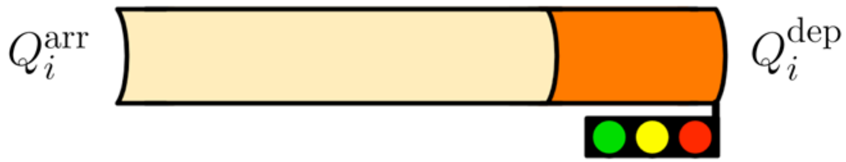




# Intersections: Modelling

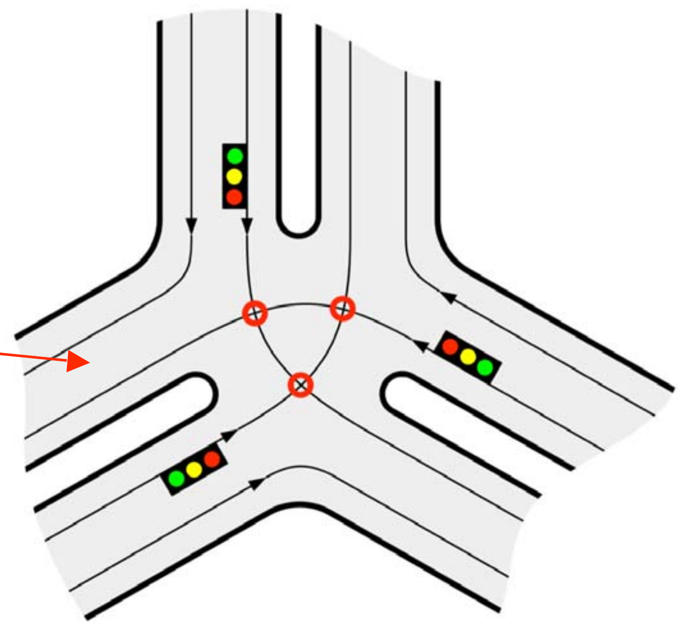
- Traffic light
  - Additional side condition

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

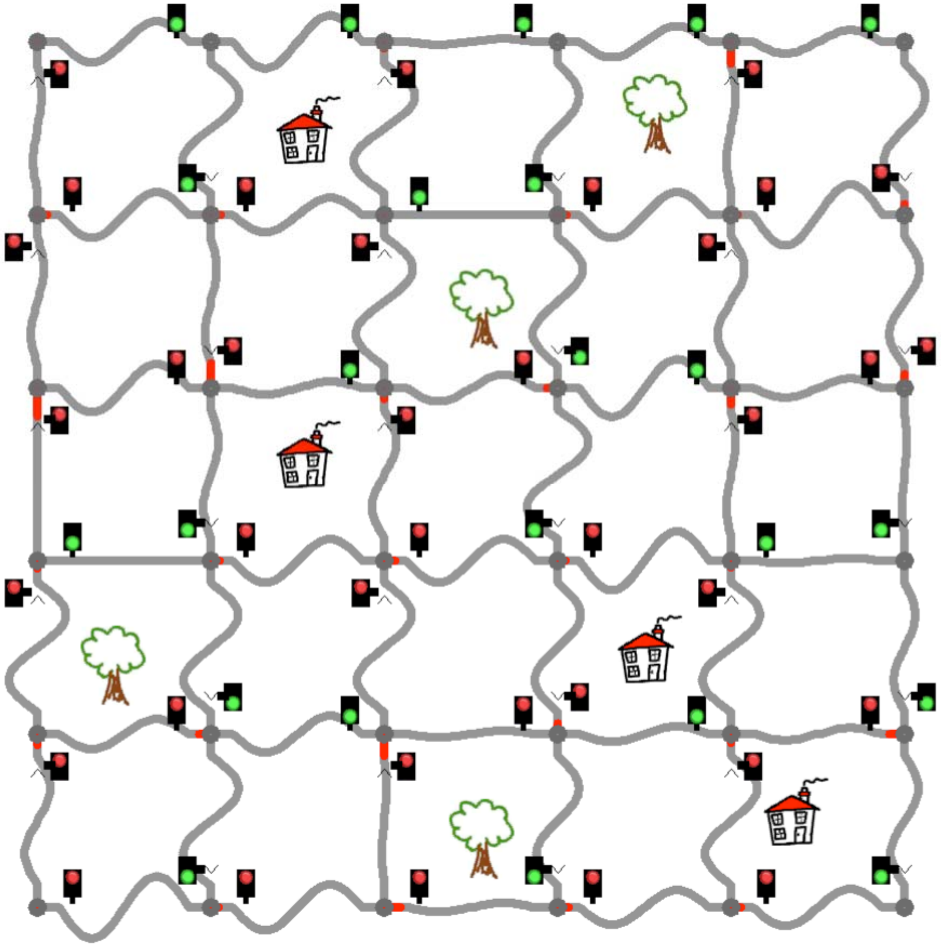



$0 \leq g(t) \leq 1$

- 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



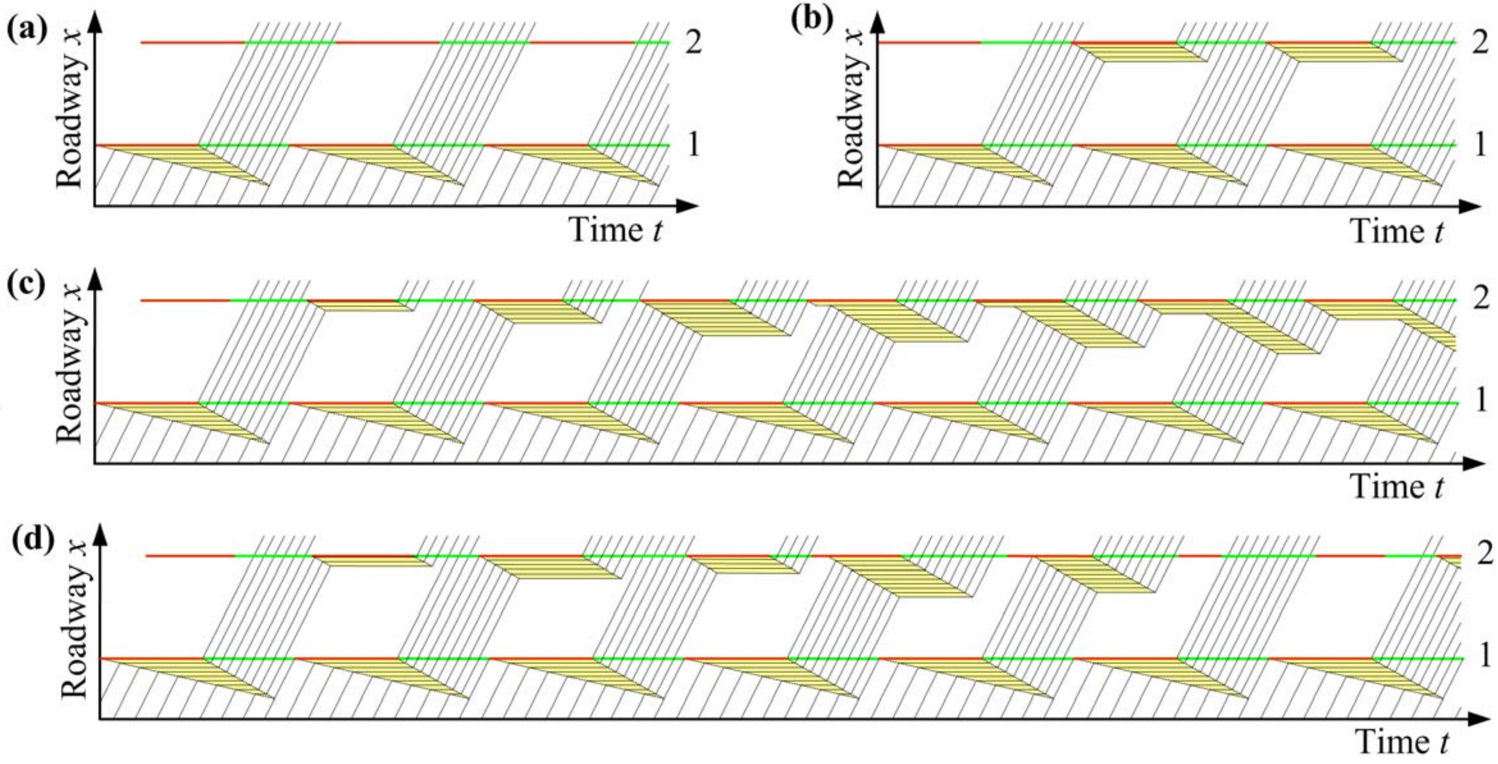
# Interdependence of Subsequent Intersections

Non-optimal phase shift

Green wave

Different cycle times

Stochastic switching



# 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!)

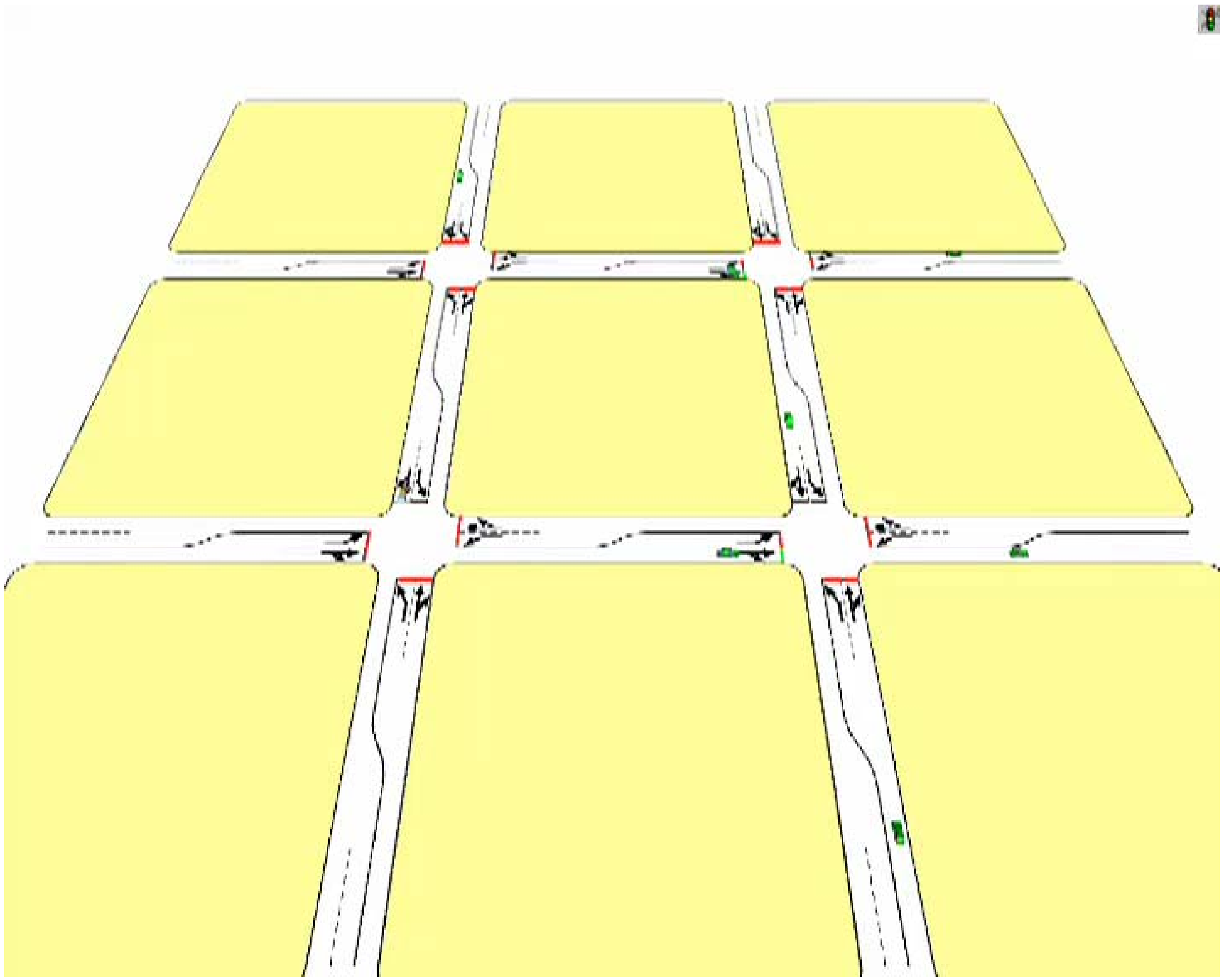
**Optimization problem is dominated by non-linearities and NP hard!**

# 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

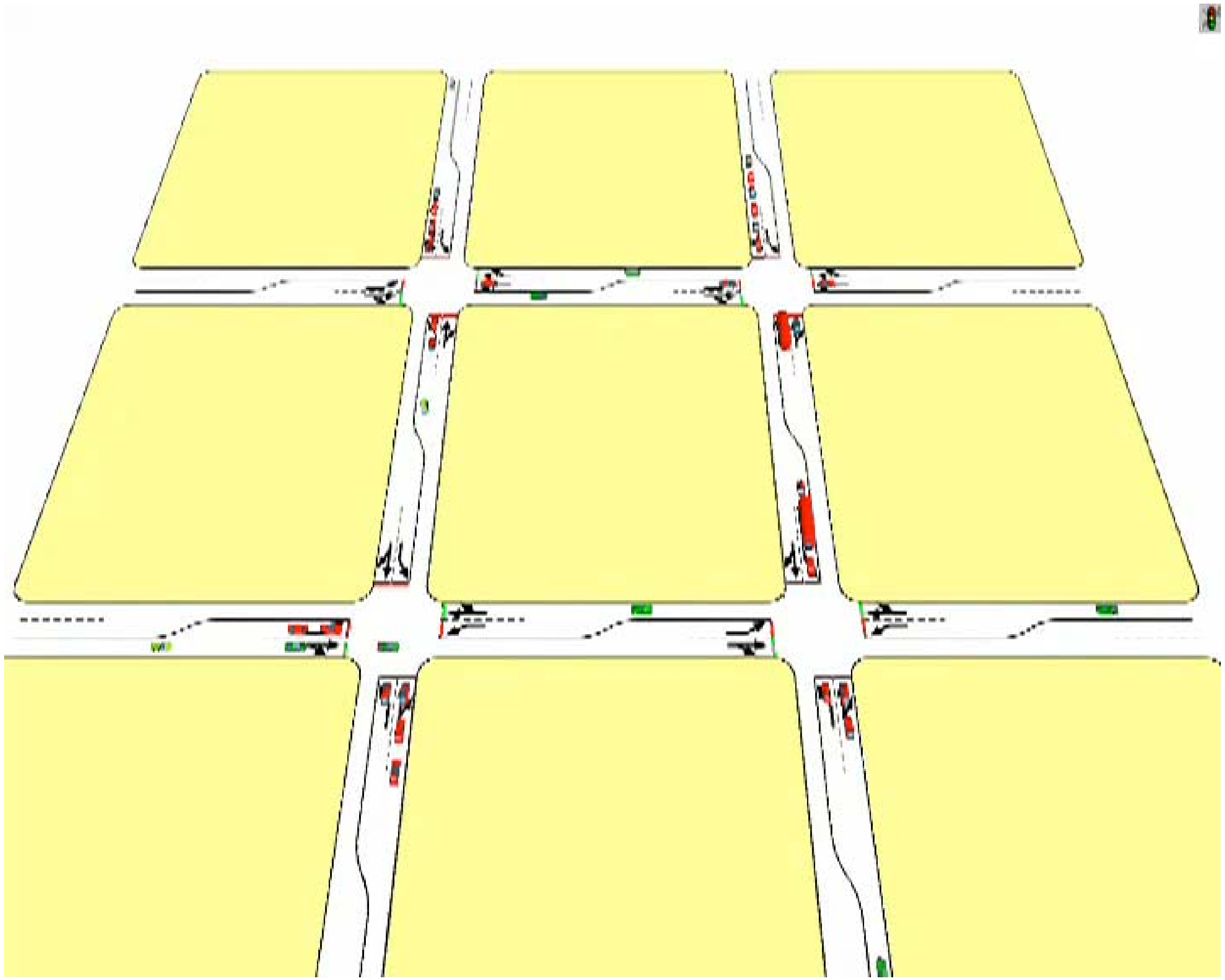


# Operation Regimes of Traffic Light Scheduling

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

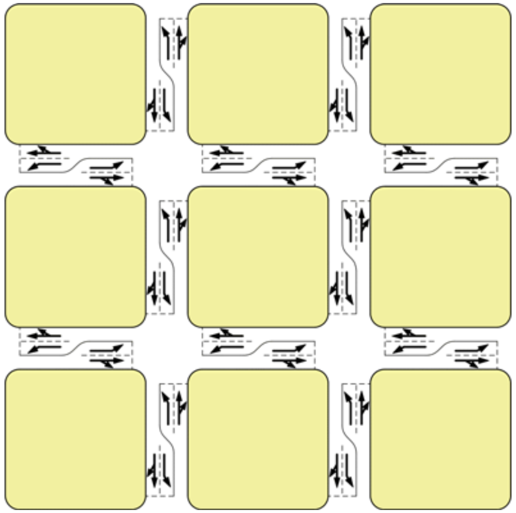
- Demand below and possibly close to capacity
- Simultaneous arrivals and, therefore, conflicts of usage likely
- Waiting times are unavoidable. Hence, vehicle platoons are forming
- The goal is to minimize waiting times
- Serving platoons rather than single vehicles increases throughput!
- Longer standing 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.

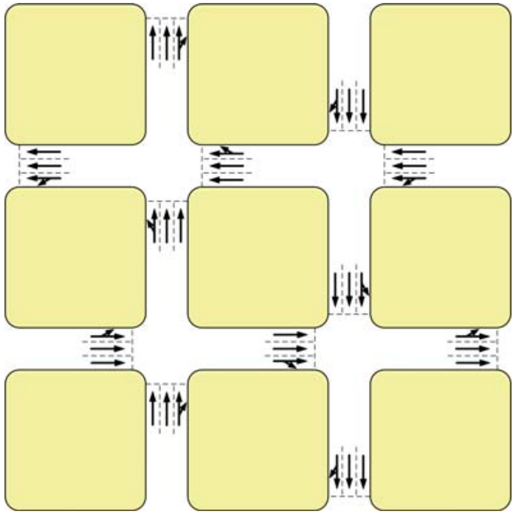
# Emergence of Green Waves



# Operation Regimes of Traffic Light Scheduling

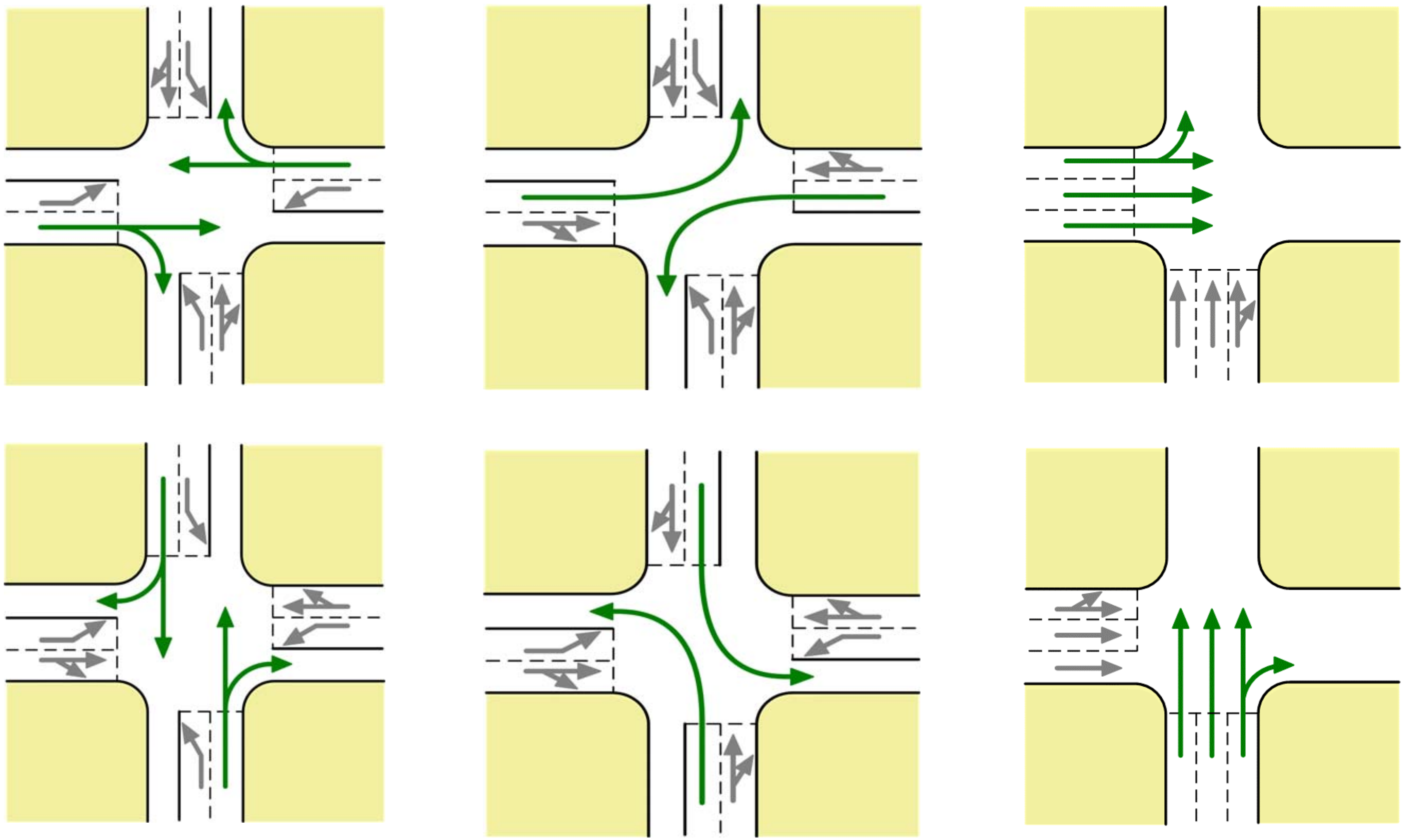
## III. Condensed, Congested, Queue-Dominated Regime



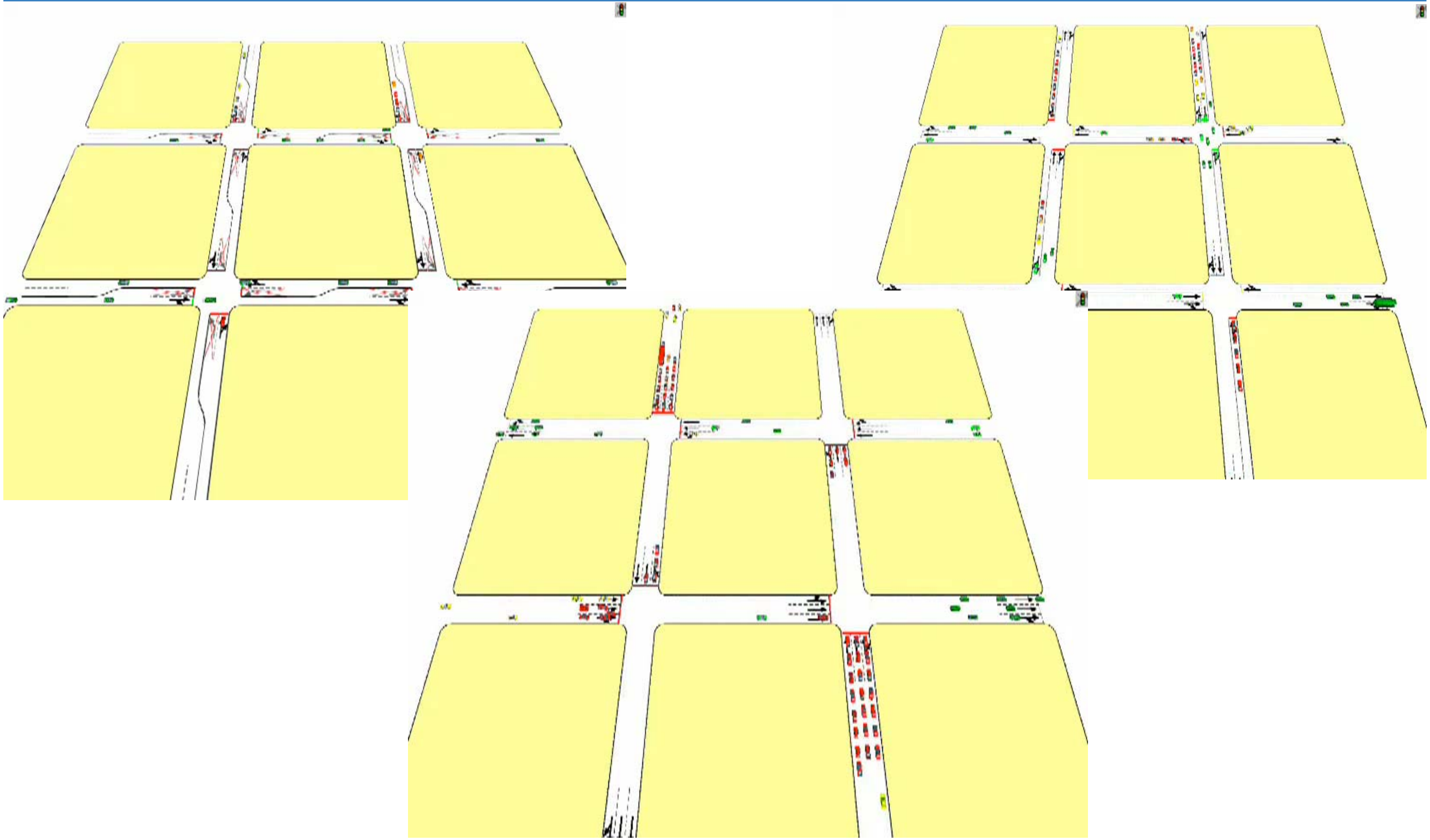


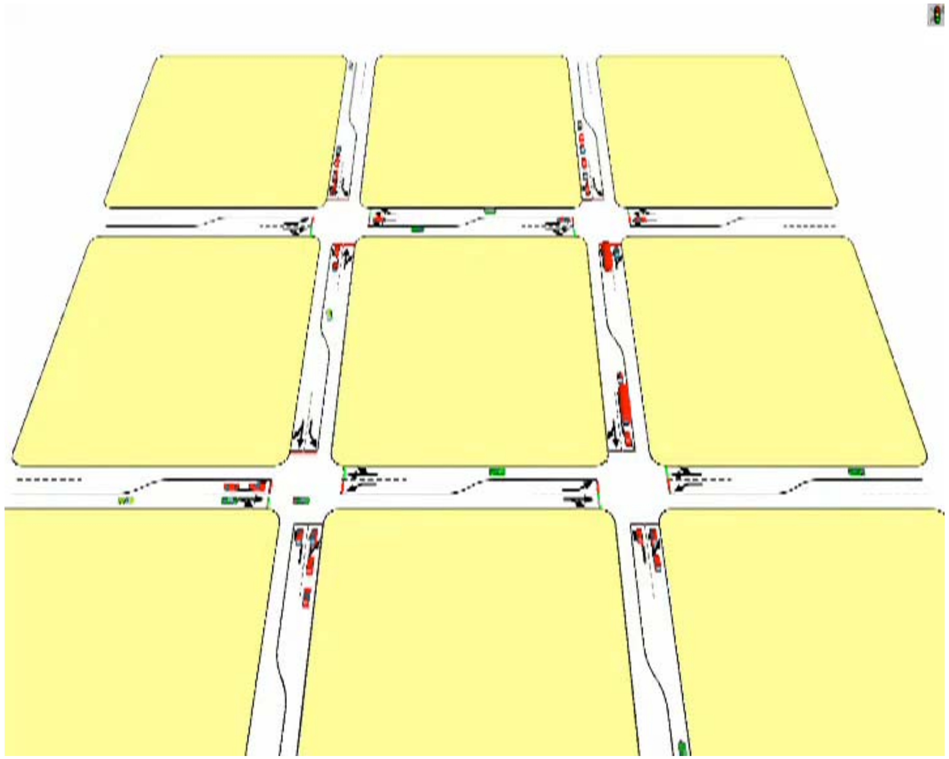
- Demand above capacity
- Goal becomes flow maximization, as queues form in all directions
- Application of flow bundling principle (similarly to platoon formation) is recommended: Reduction of service/turning directions, i.e. of heterogeneity, increases capacity

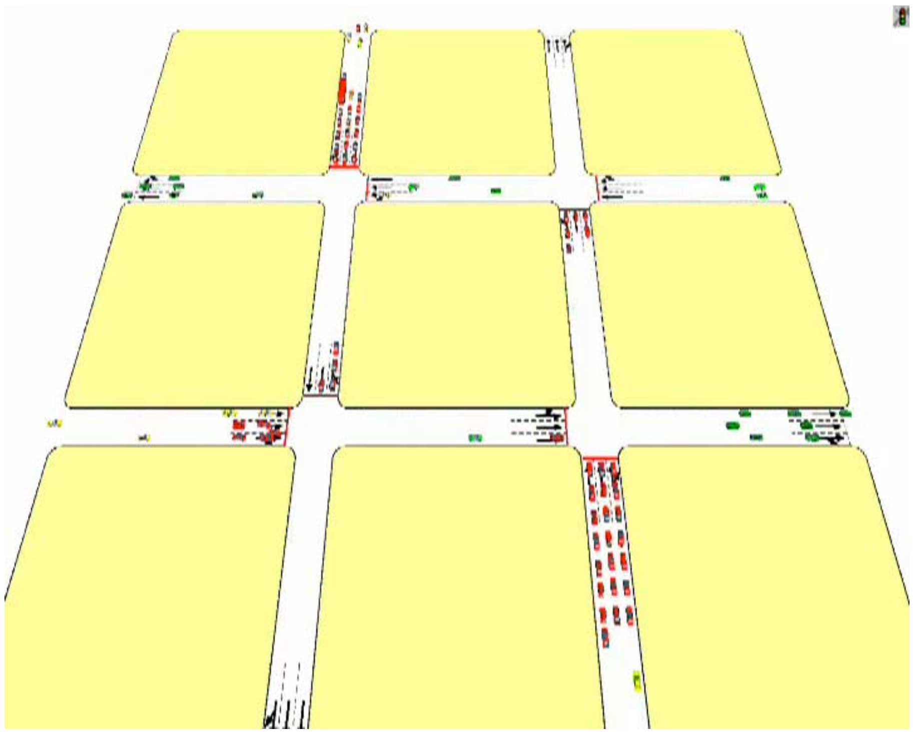
# Reduction of Traffic Phases Means Increase of Capacity



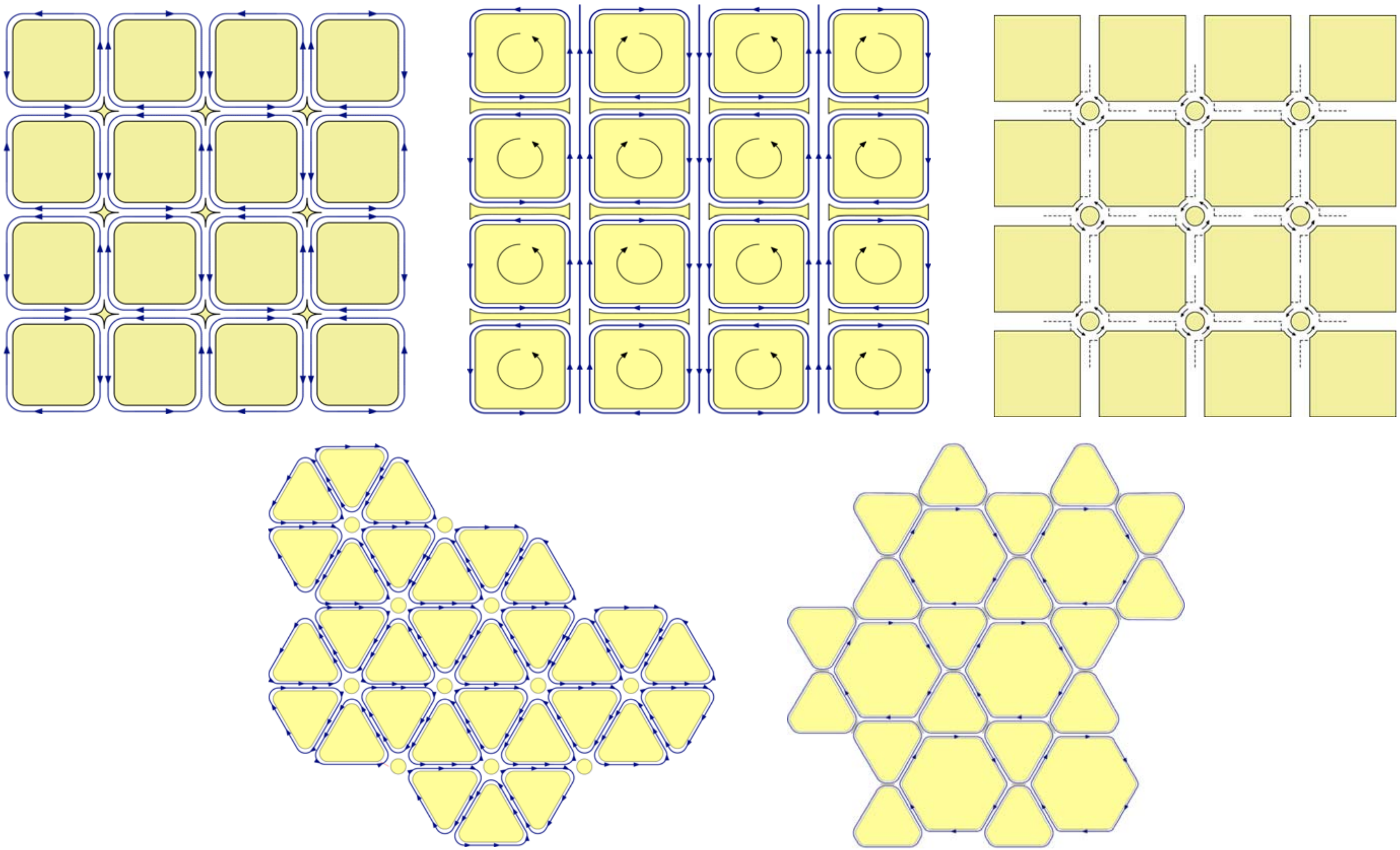
# Reorganizing the Traffic Network







# Intersection-Free Designs



# Self-Organized Traffic Flow at Unsignalized Intersections

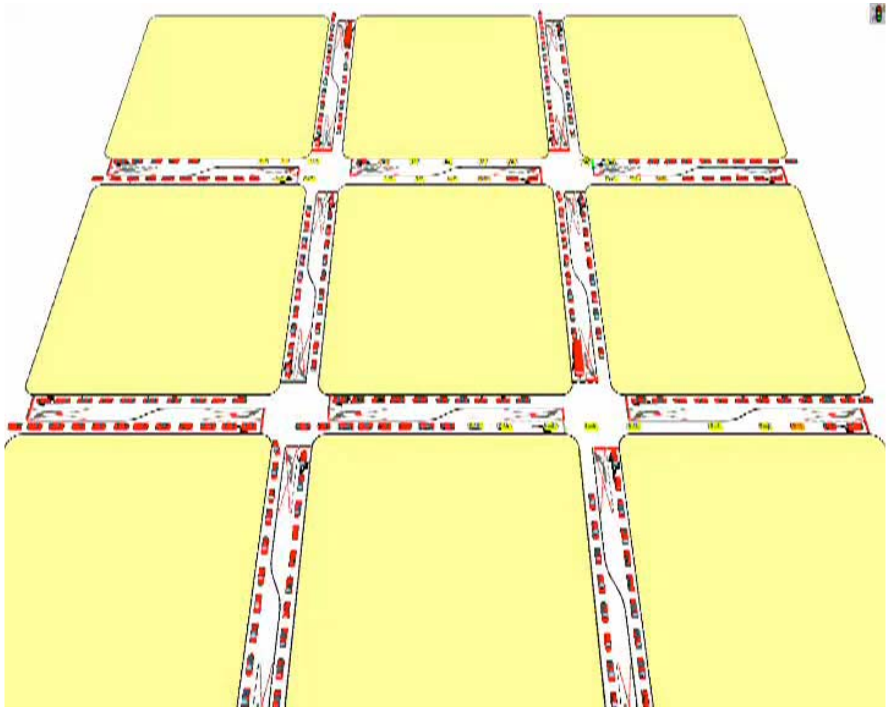
# Operation Regimes of Traffic Light Scheduling

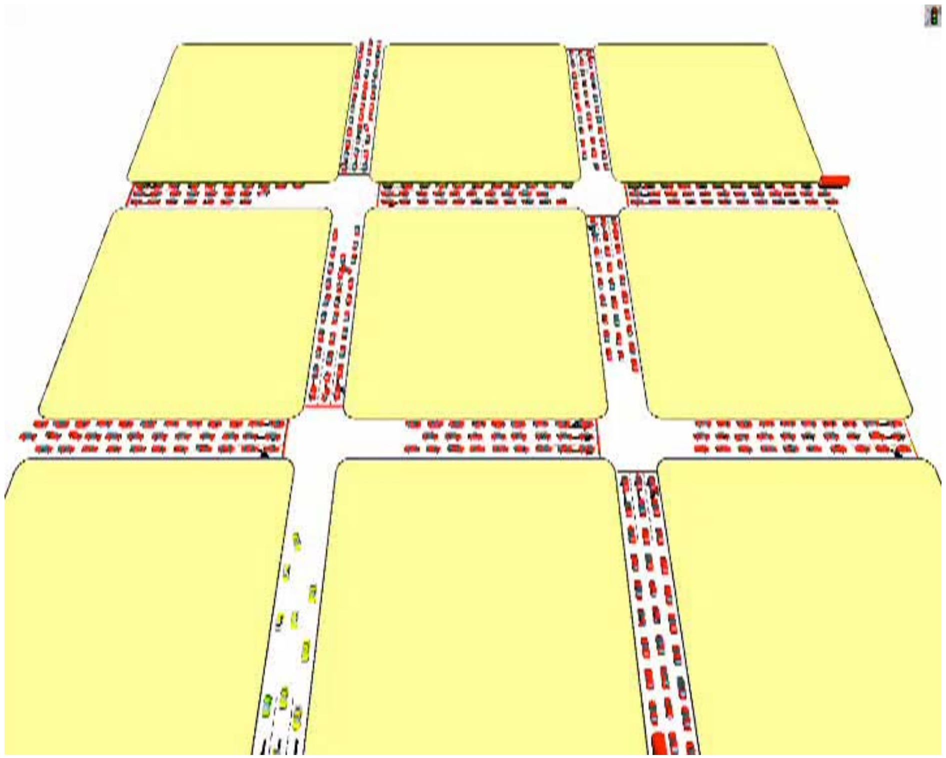
## IV. Bubble Flow, Heavily Congested Gap Propagation Regime

- 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

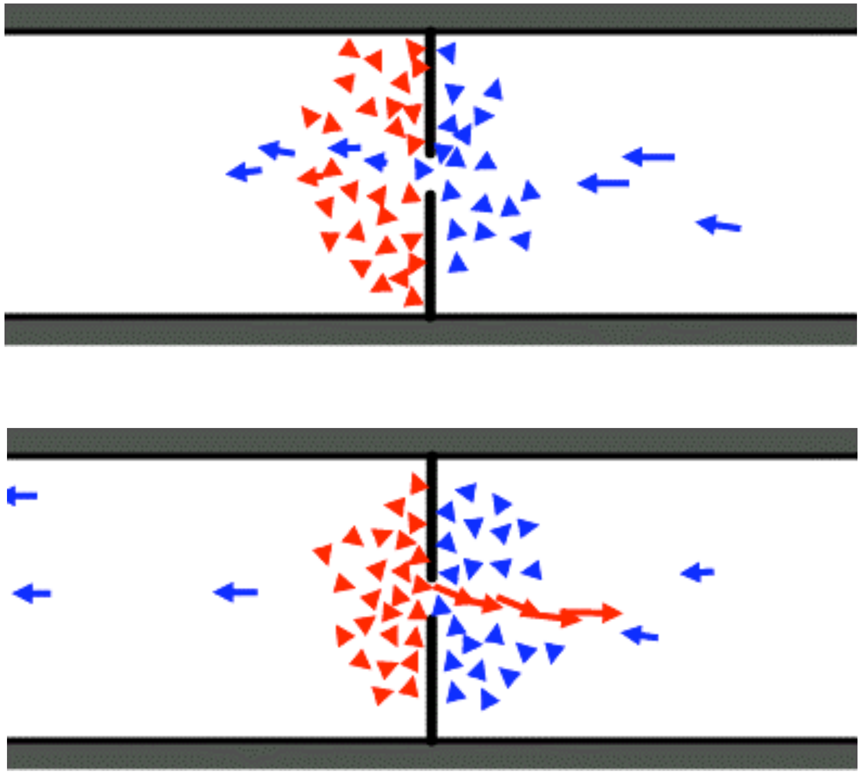
## Objectives:

- 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

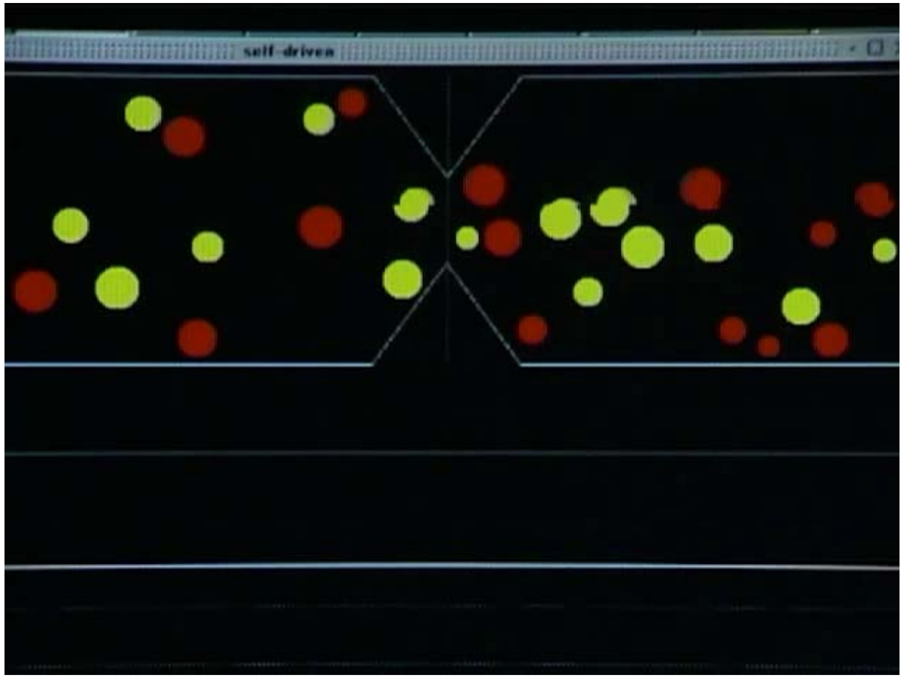
## Expected Advantages:

- 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

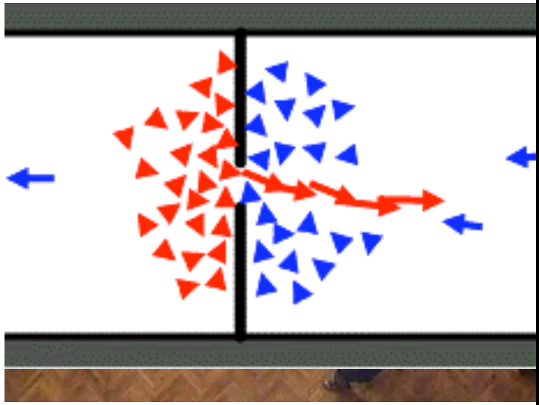


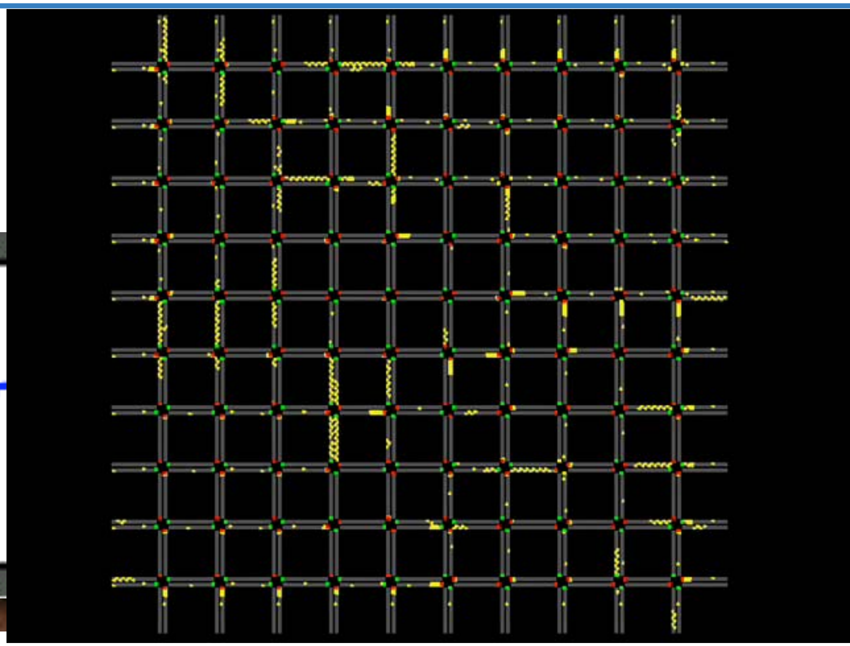
- Pressure-oriented, autonomous, distributed signal control:
  - Major serving direction alternates, as in pedestrian flows at intersections
  - Irregular oscillations, but ‘synchronized’
- In huge street networks:
  - ‘Synchronization’ of traffic lights due to vehicle streams spreads over large areas

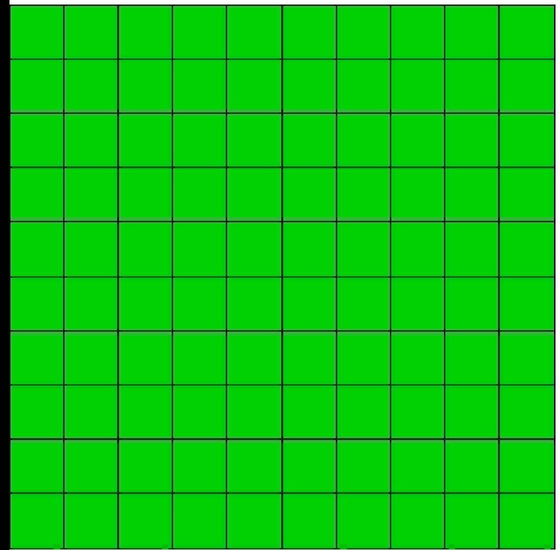


# Decentralized Concept of Self-Organized Traffic Light Control

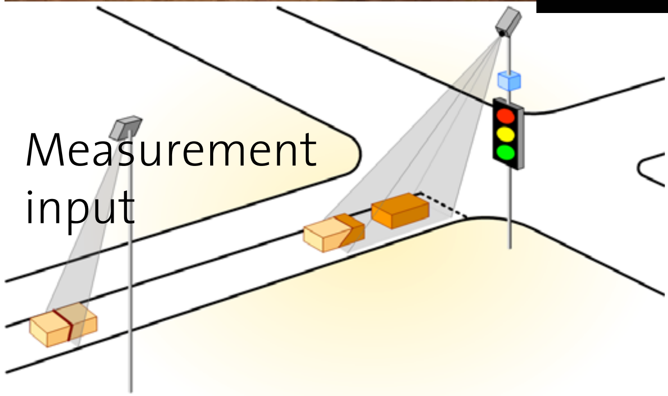
Inspiration: Self-organized oscillations at bottlenecks





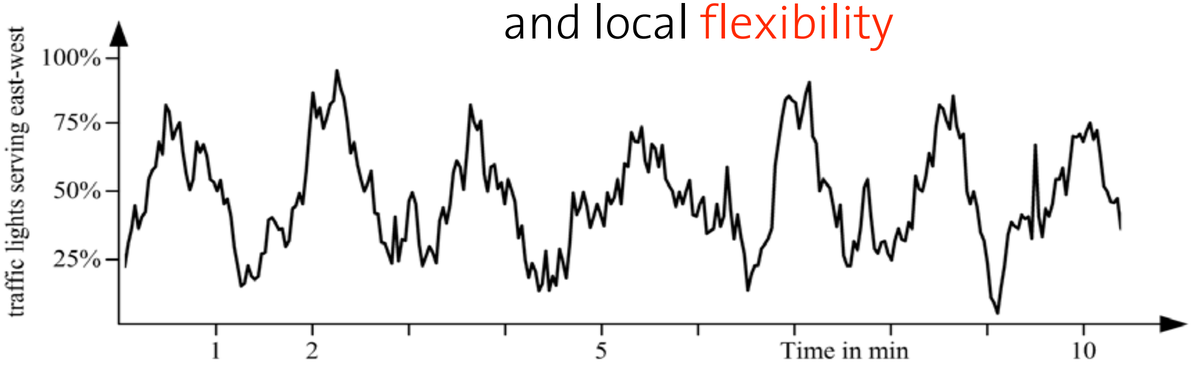


Measurement input



Published in *JSTAT* (2008)

Optimal compromise between coordination and local flexibility

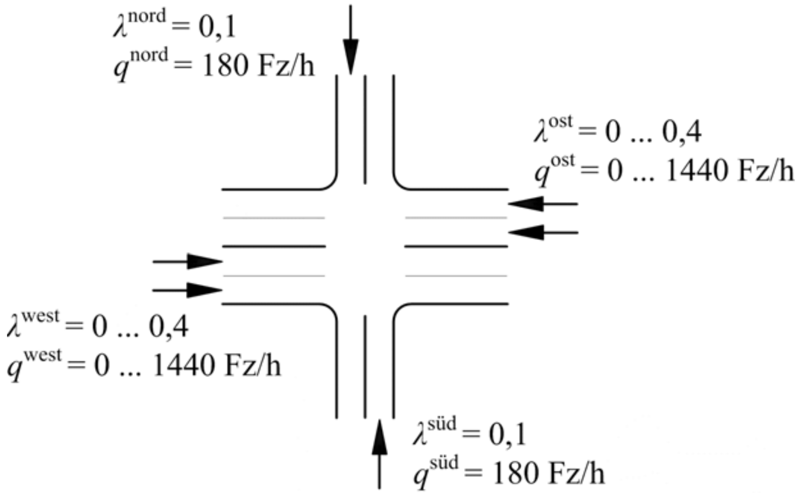


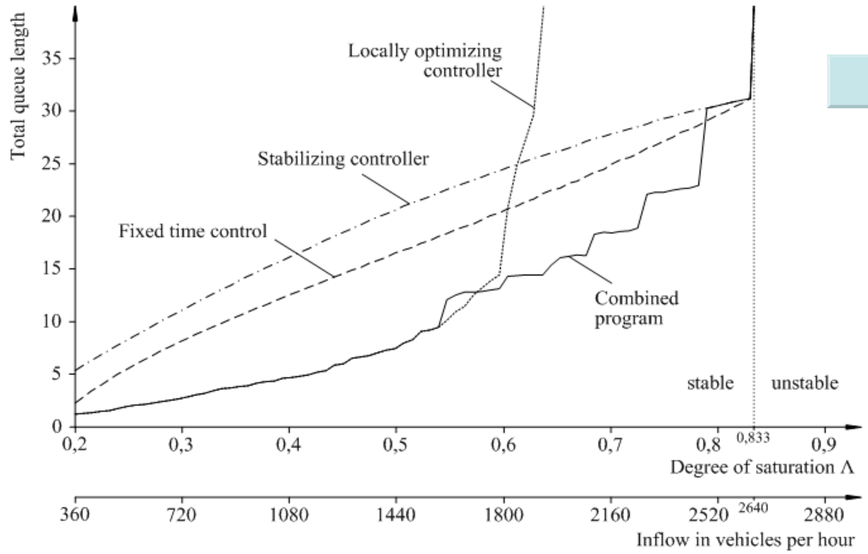
# Properties of the Self-Organized Traffic Light Control

- 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

# Simulation Study: Isolated Intersection (1)

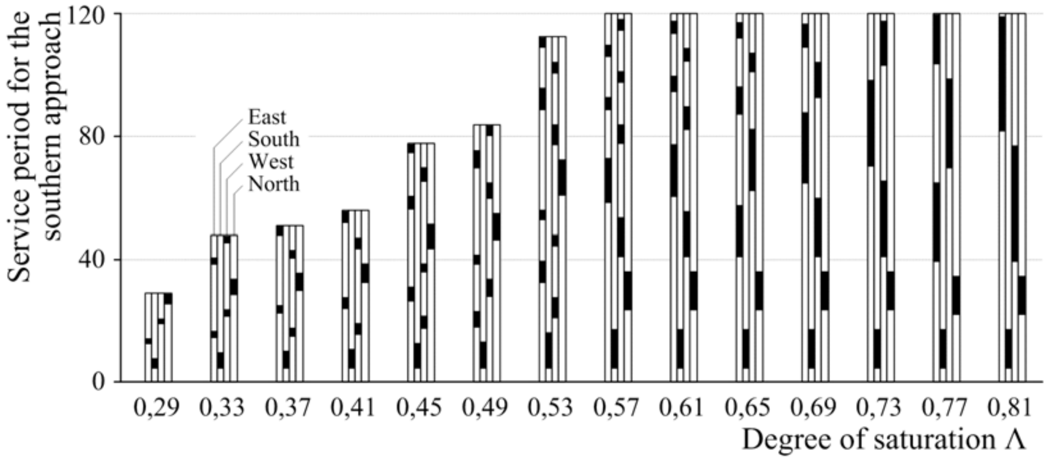
With constant arrival rates:



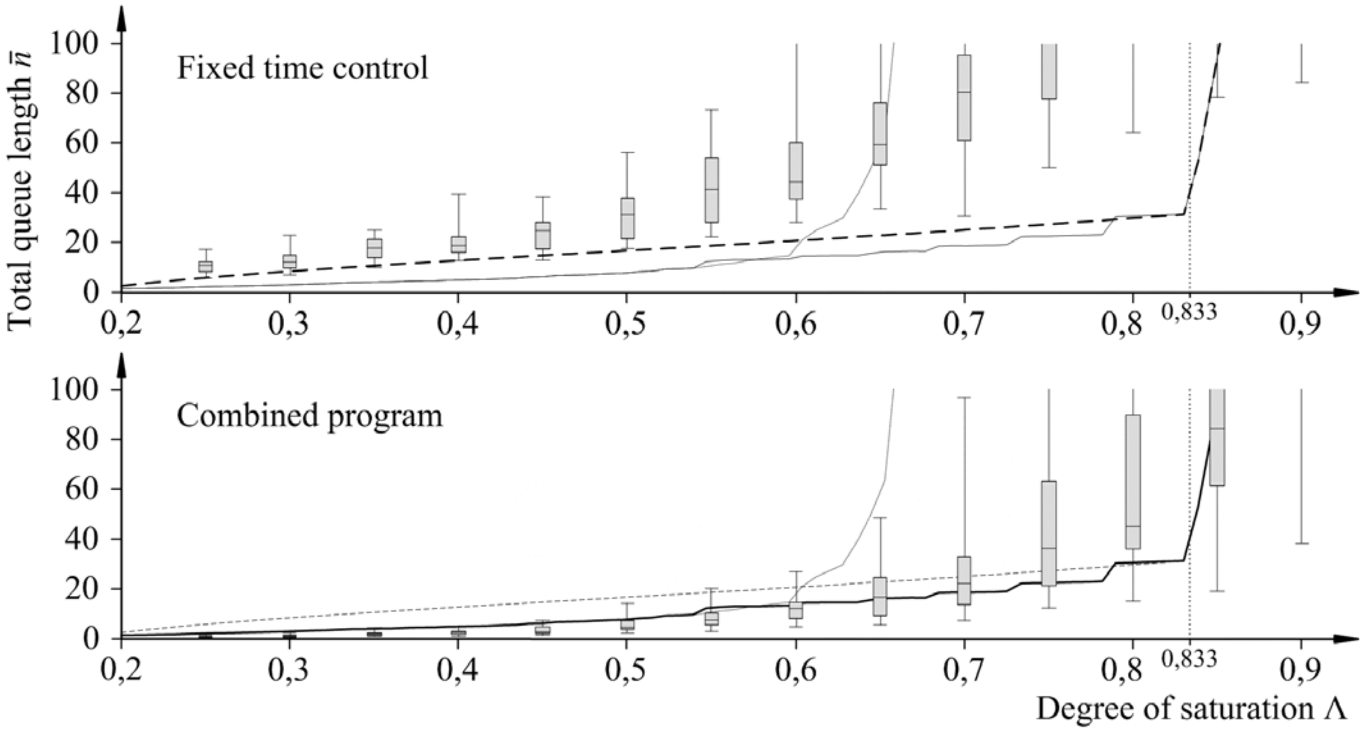

The switching sequence adapts to the arrival patterns.

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



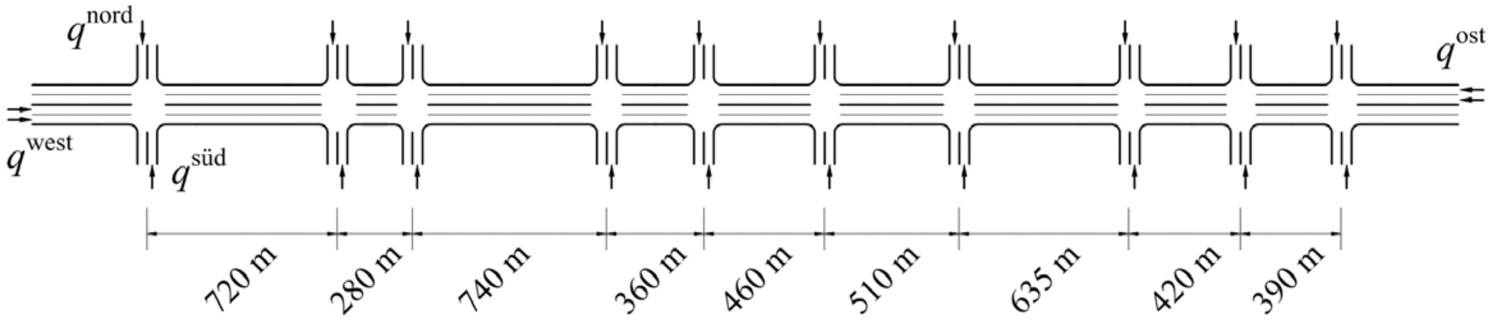
# Simulation Study: Isolated Intersection (2)

With stochastic arrivals:

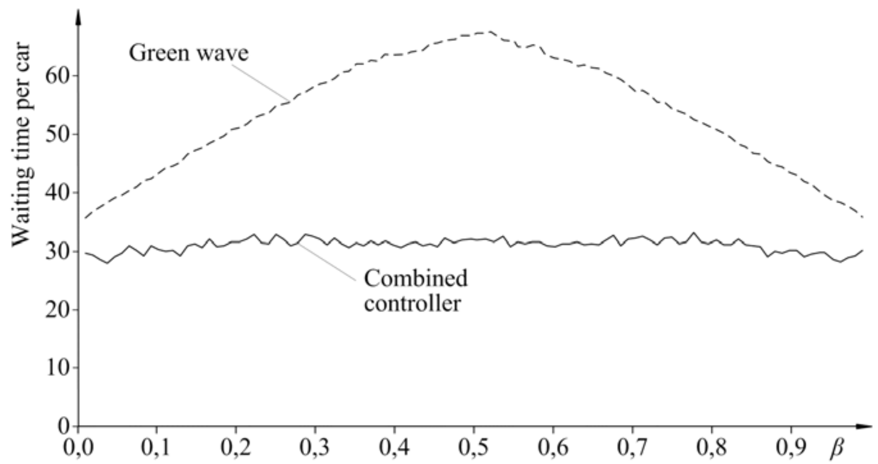



Due to the flexibility, we observe a reduction in both, the total **waiting time** and its **variance**.

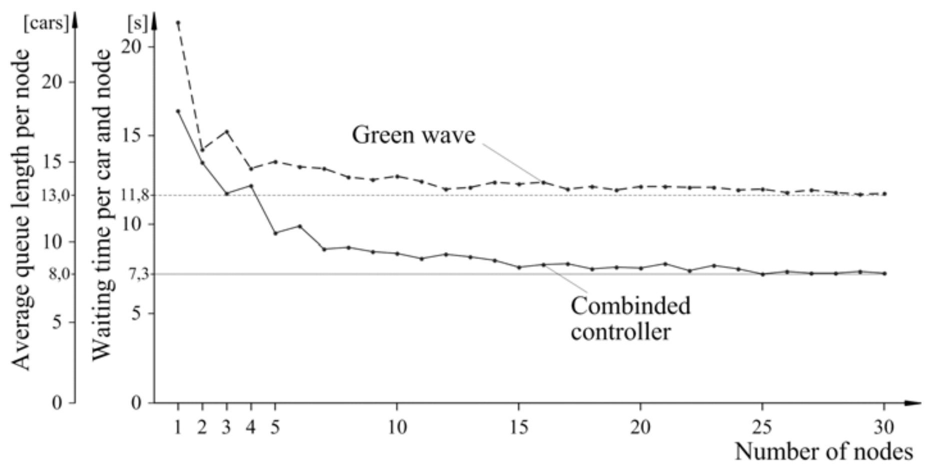
# Simulation Study: Coordination along an Arterial (1)



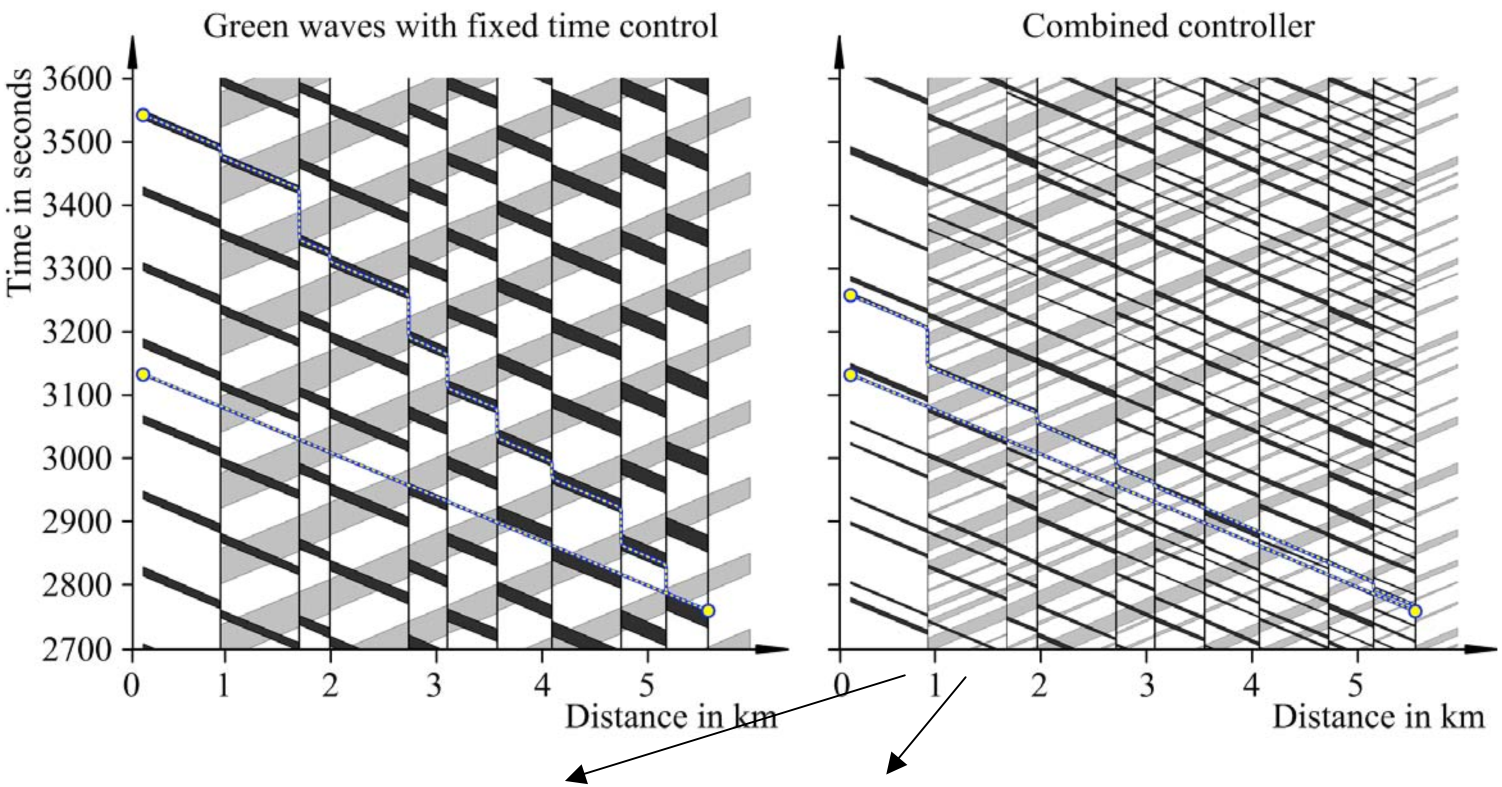

Varying the direction of the main flow




Varying the number of nodes along the arterial



# Simulation Study: Coordination along an Arterial (2)



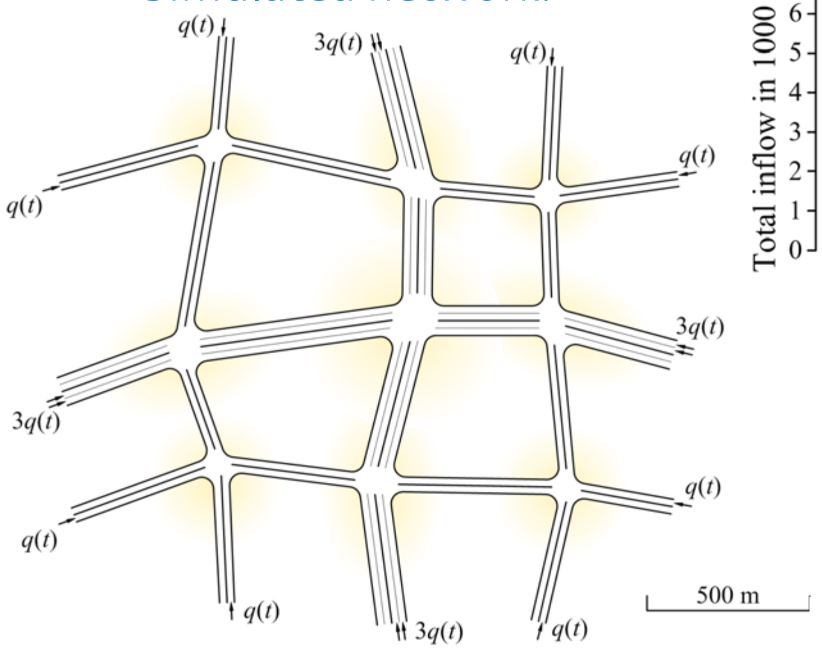

Irregular switching patterns are equalizing irregular traffic patterns, and thereby minimizing waiting times.

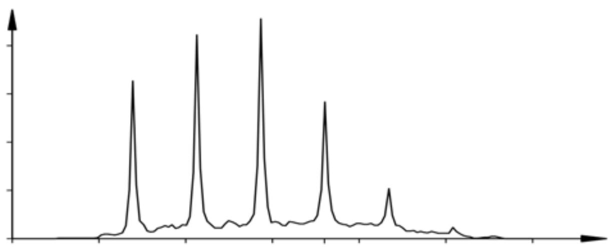
Principles:

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

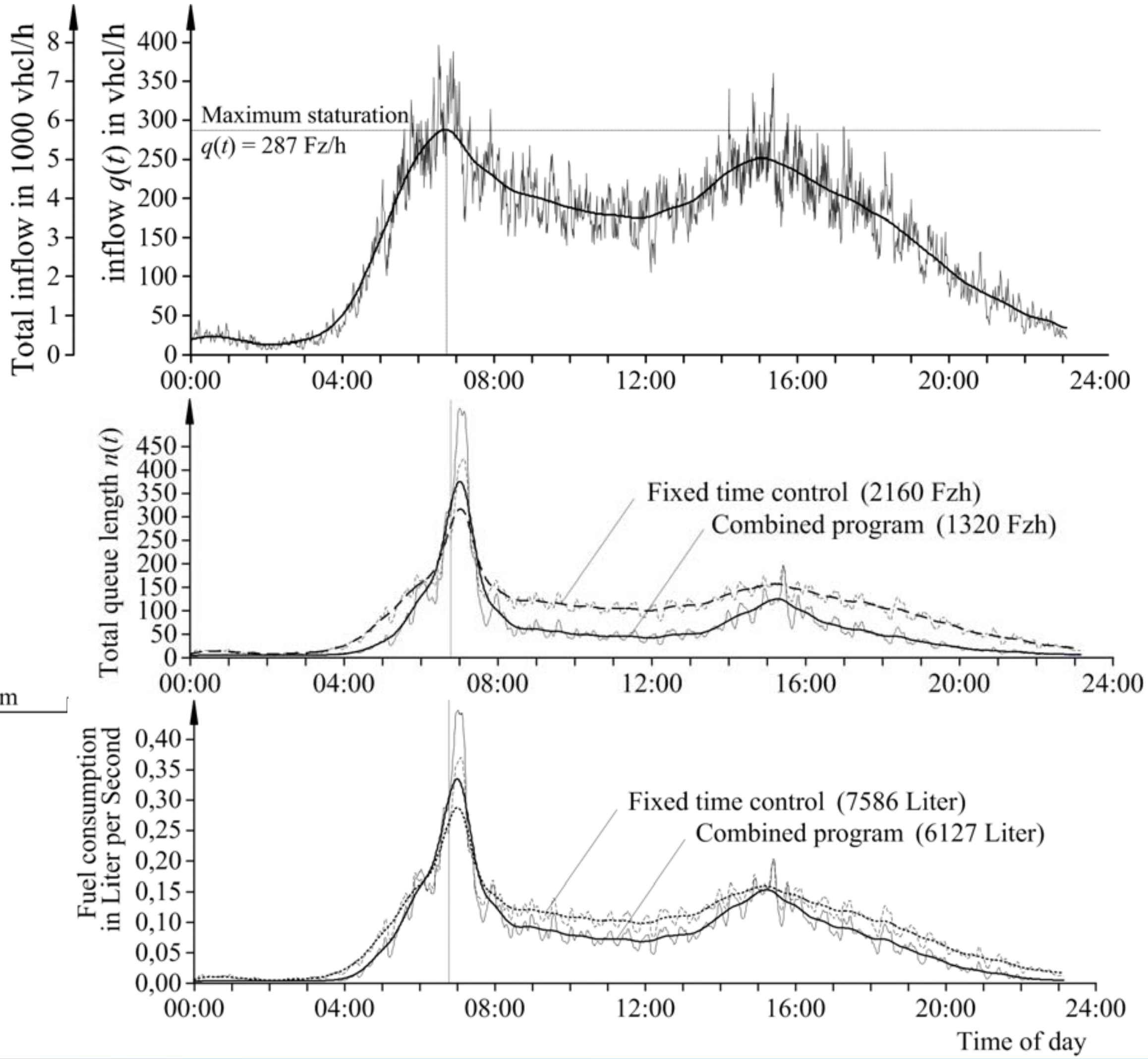
# Coordination in a Network

Simulated network:



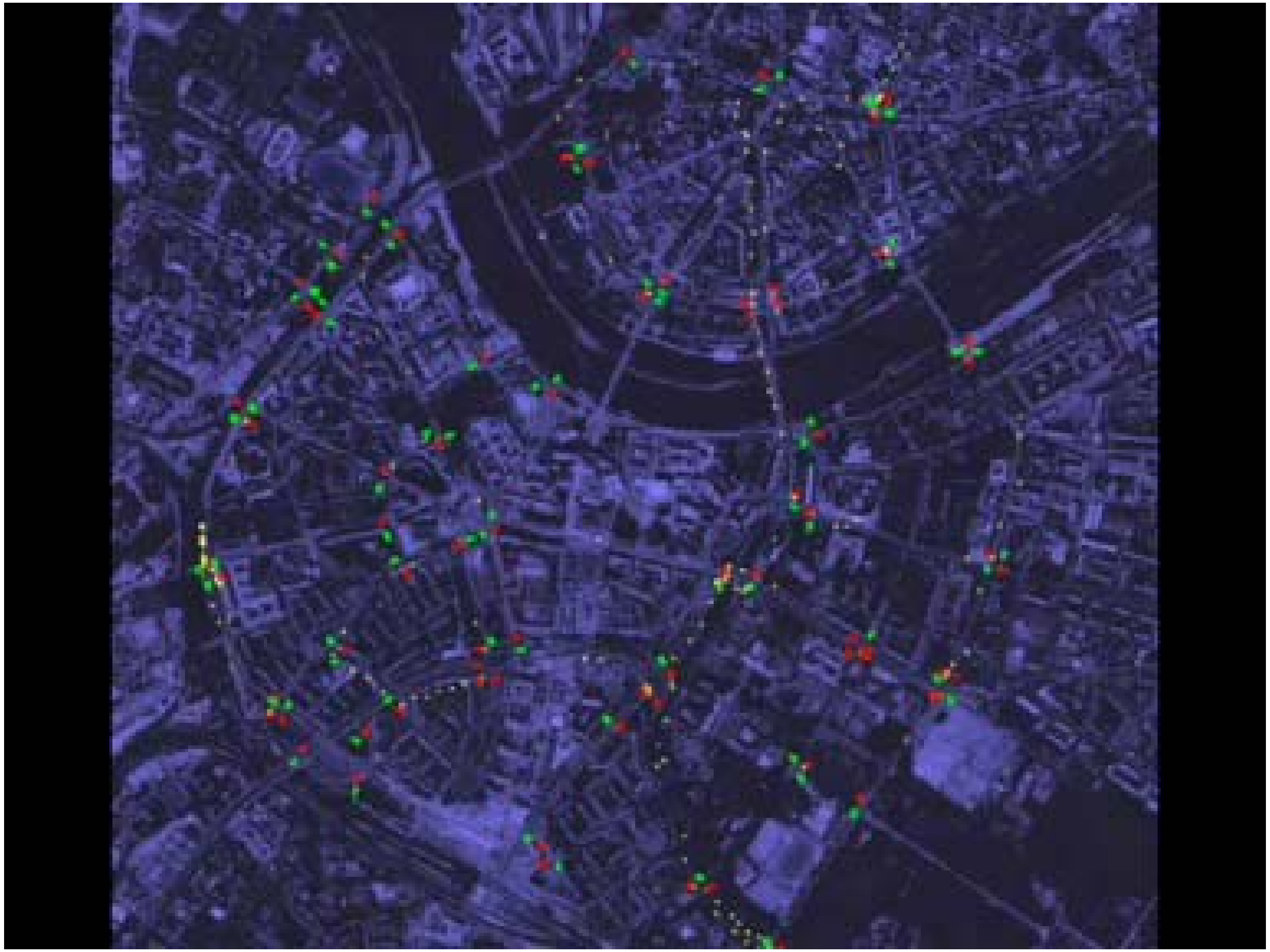



Traffic demand is specified with empirical data:

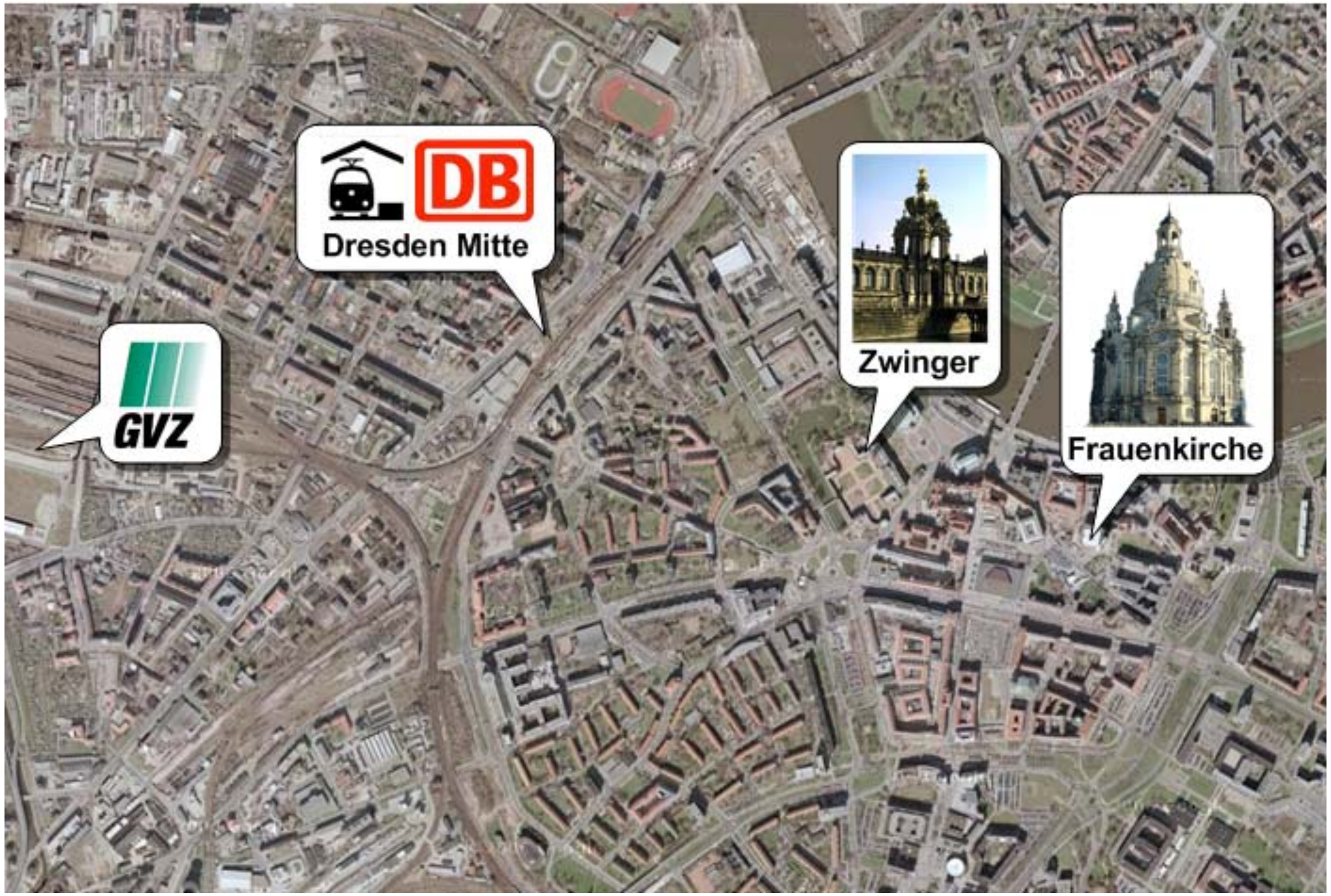


# Application Example: City Center of Dresden

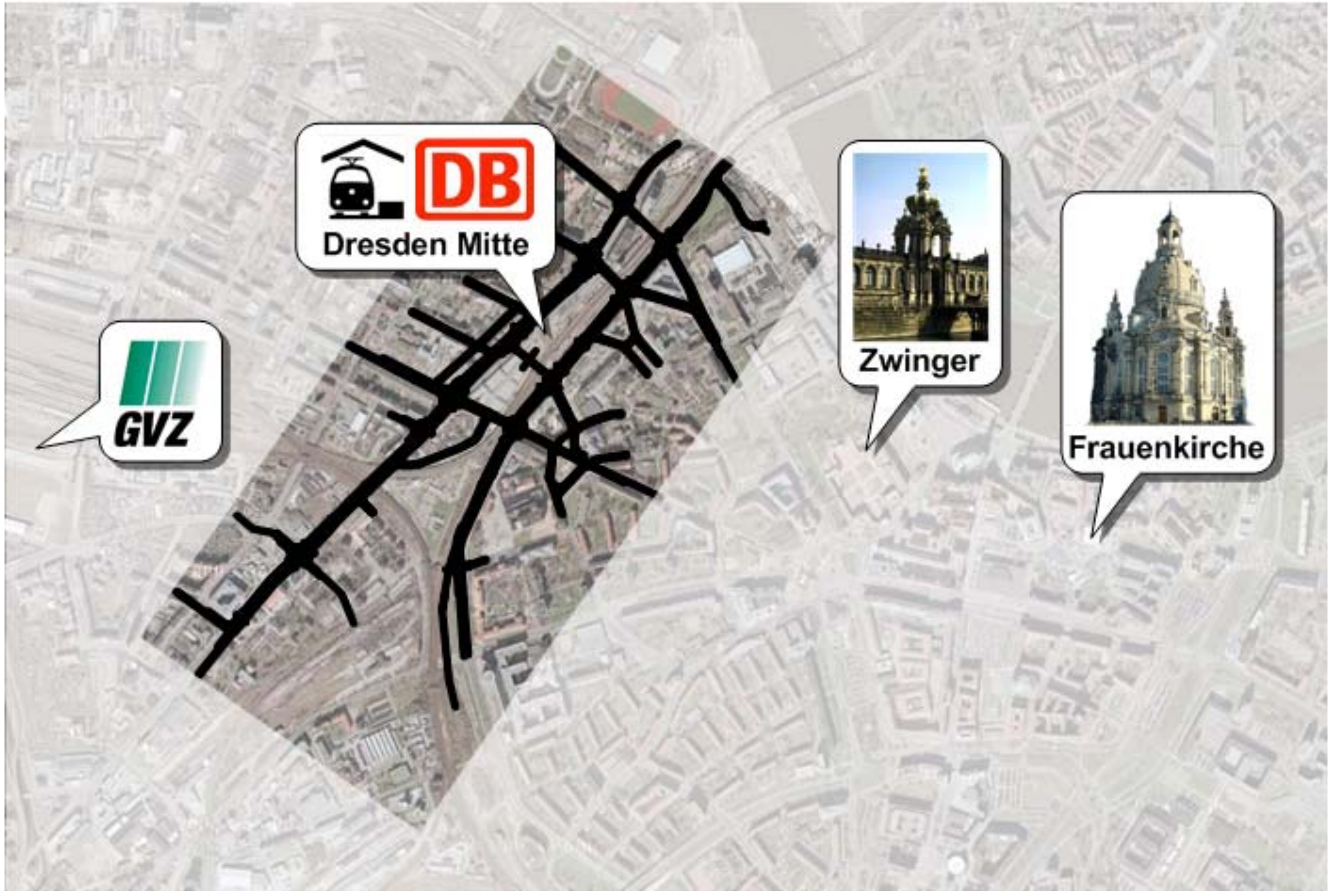
Simulation “Pirnaischer Platz”



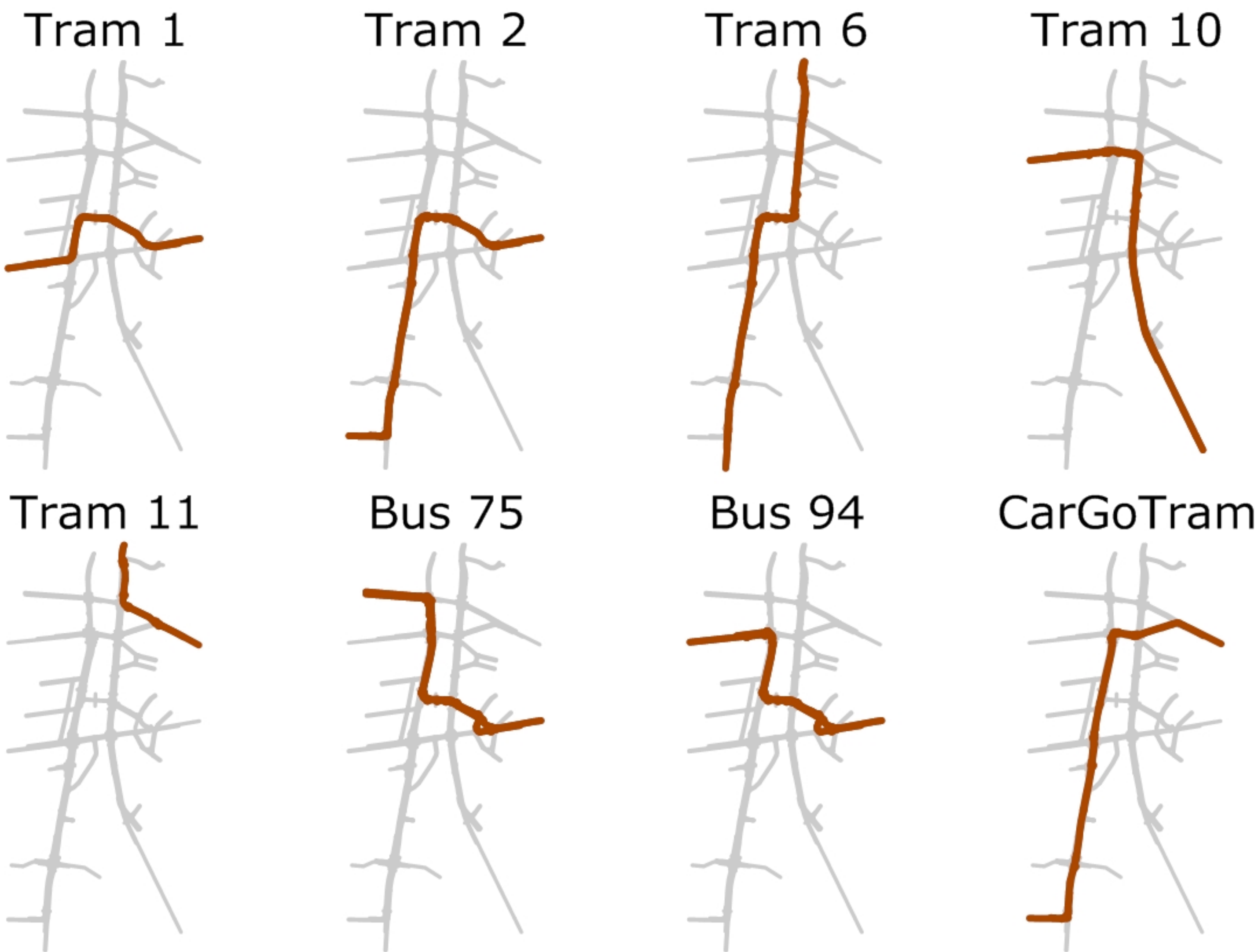
# Towards Self-Organized Traffic Light Control in Dresden



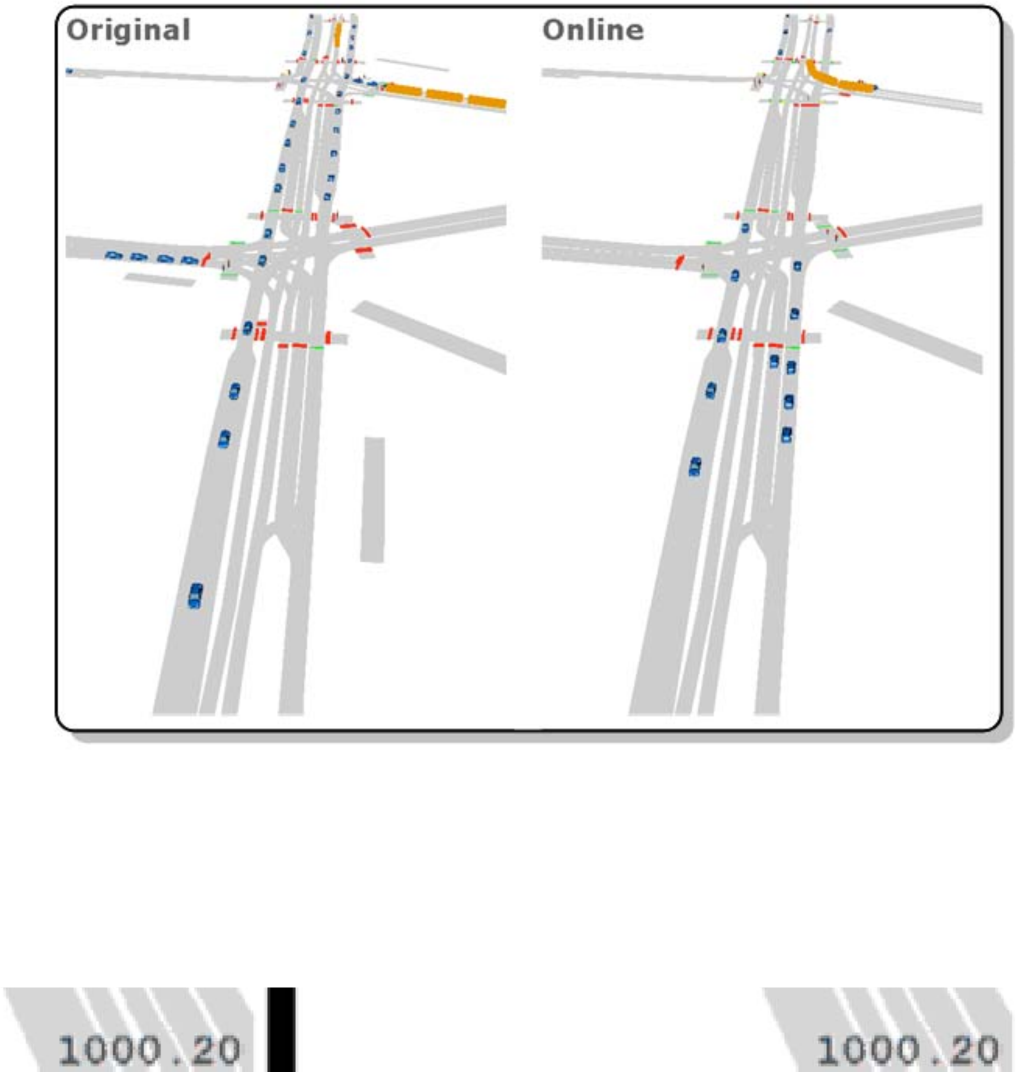
# The Measurement and Control Area



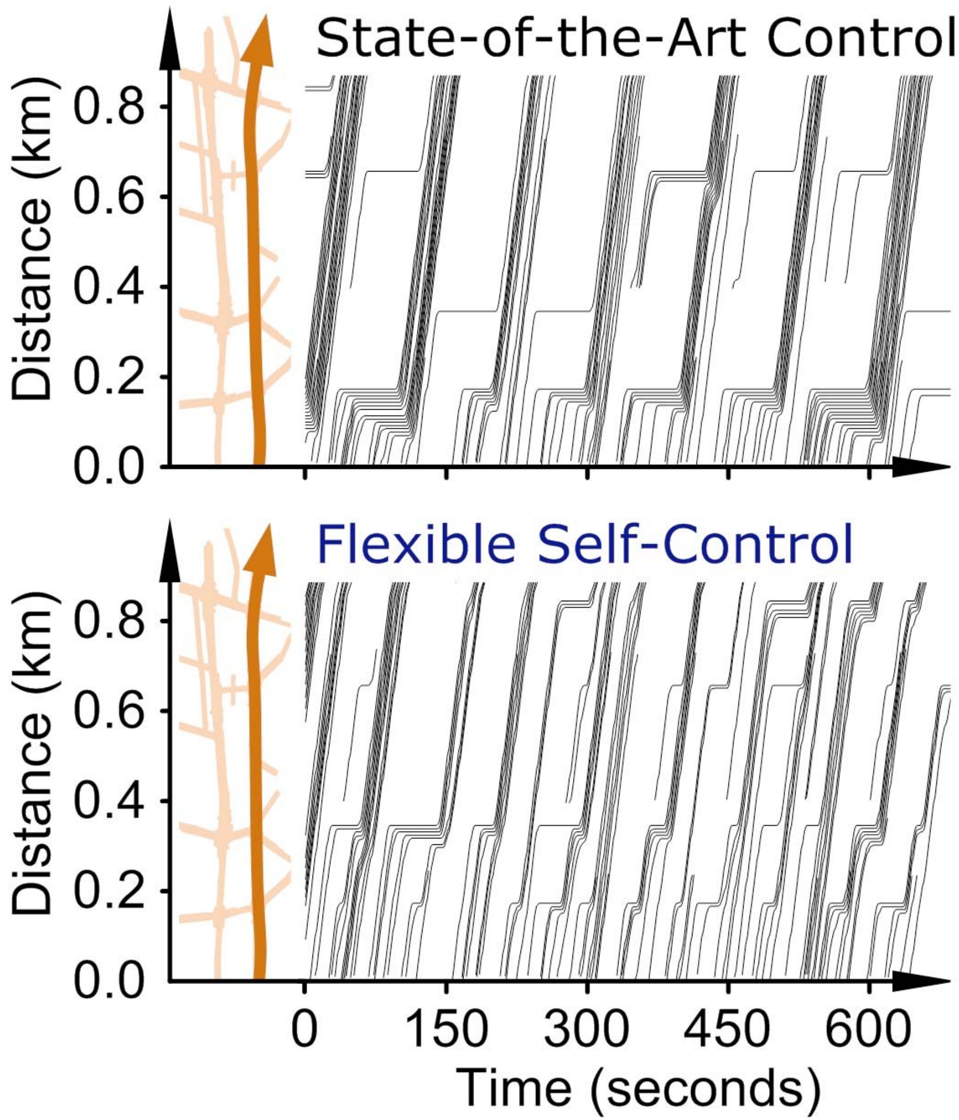
# Disturbance of Traffic Coordination by Bus and Tram Lines



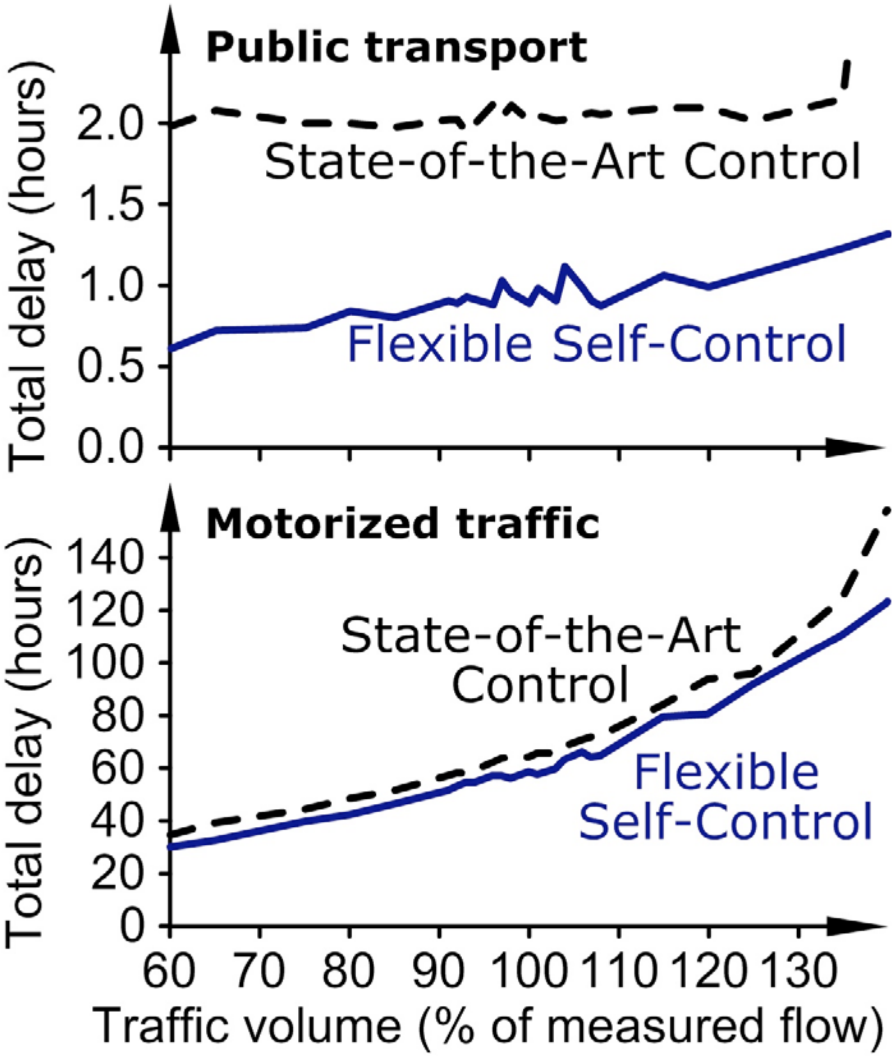
# Comparison of Current and Self-Organized Traffic Light Control



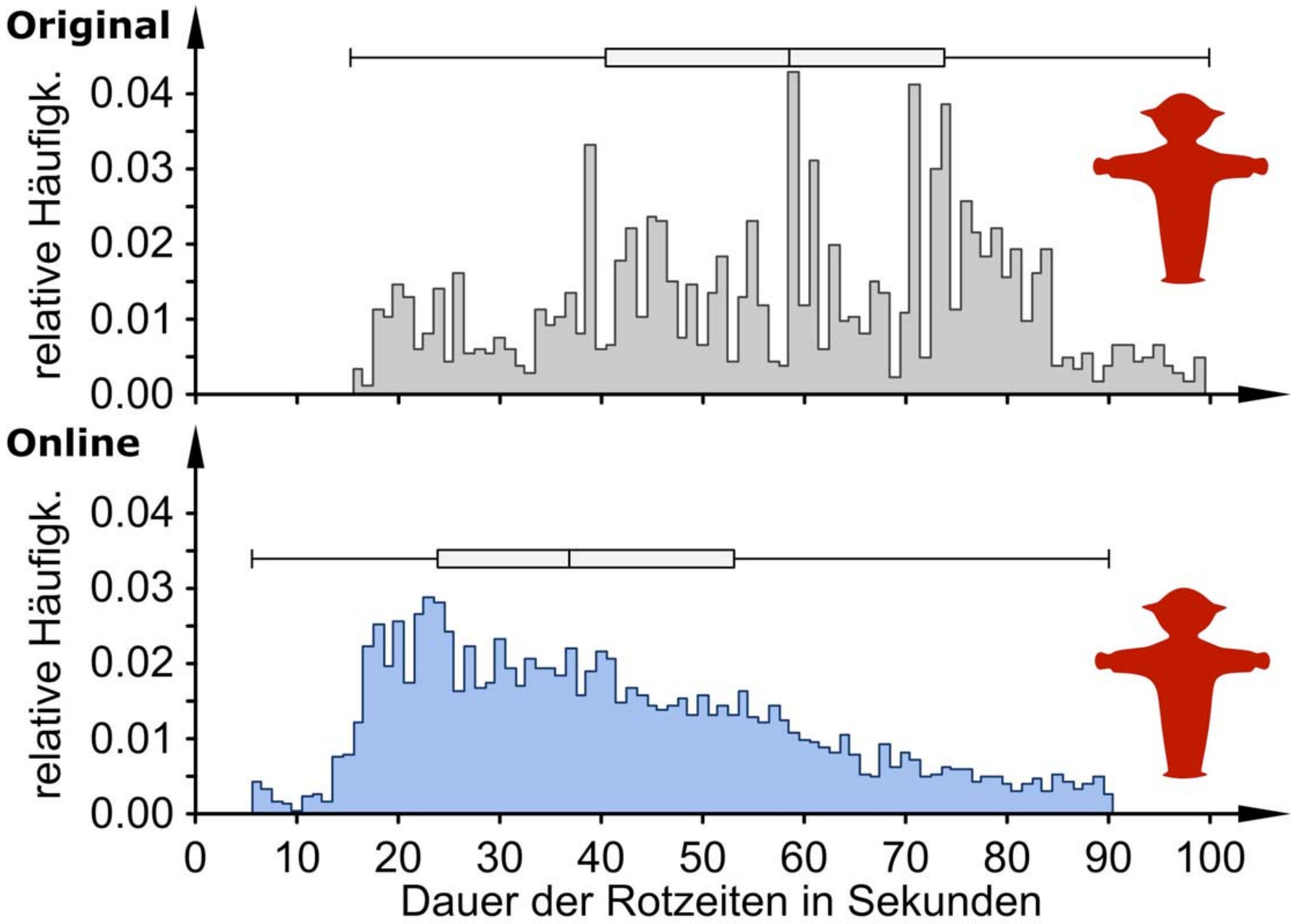
# Synchronize Traffic by Green Waves or Use Gaps as Opportunities?



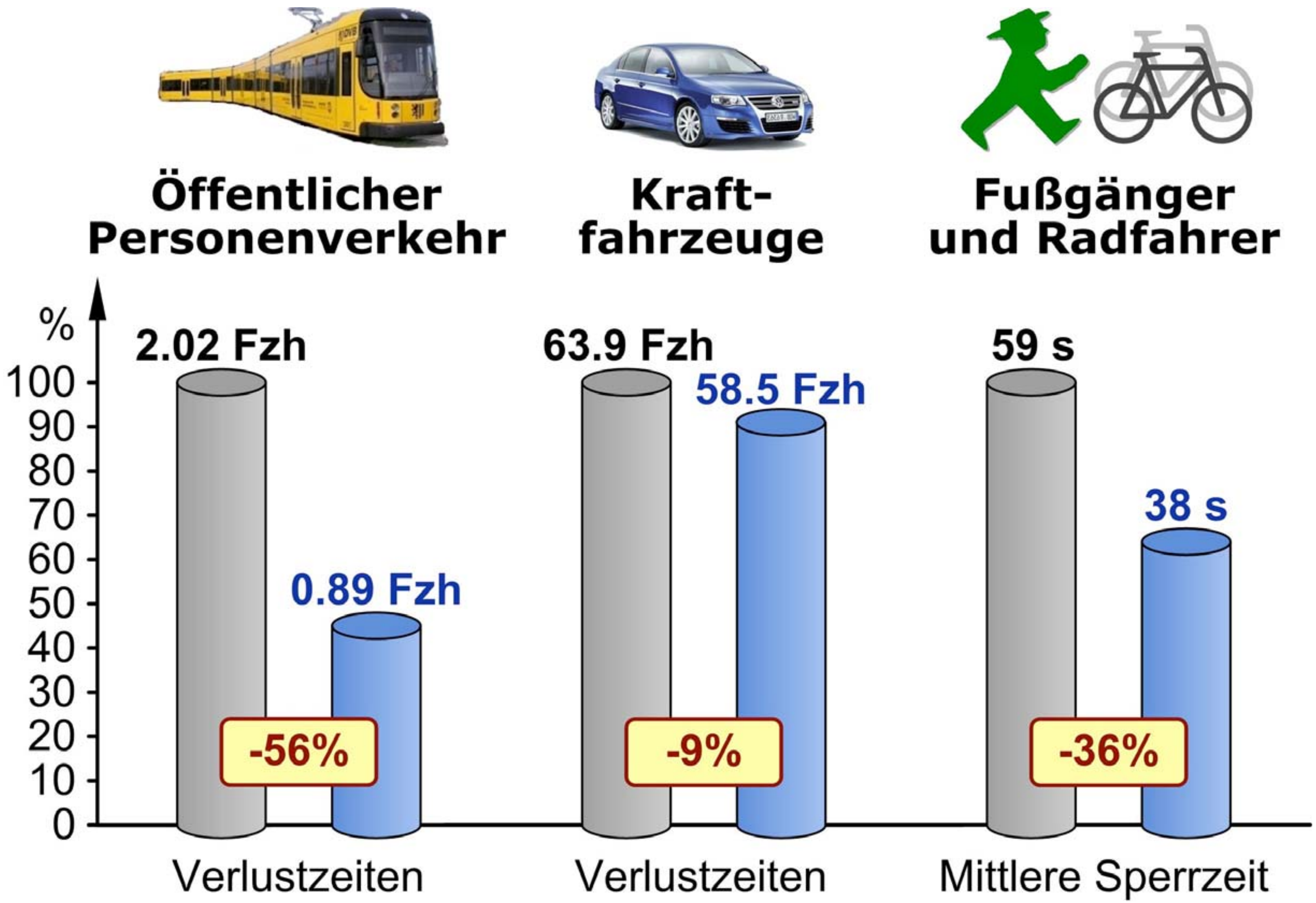
# Performance in Dependence of the Traffic Volume



# Red Time Distribution for Pedestrians

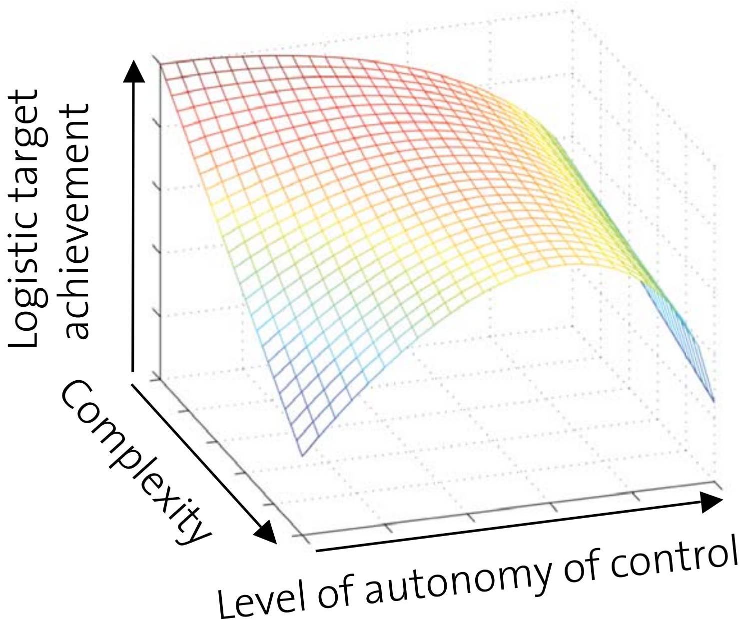


# Gain in Performance



# Centralized Control and Its Limits

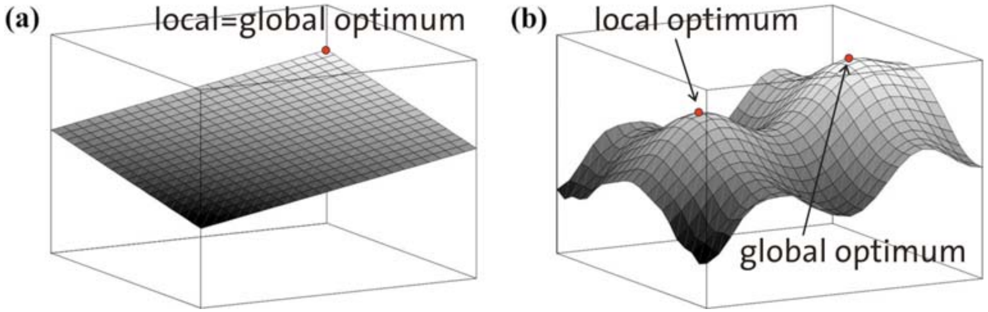
- Advantage of centralized control is large-scale coordination
- Disadvantages are due to
  - vulnerability of the network
  - information overload
  - wrong selection of control parameters
  - delays in adaptive feedback control
- Decentralized control can perform better in complex systems with heterogeneous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



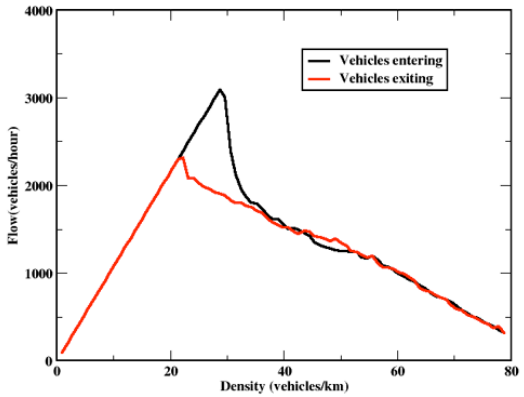

(Windt, Böse, Philipp, 2006)

# Discussion: Weaknesses of Classical Optimization

- Optimization routine may get stuck in a local optimum
- One can only optimize for one goal at a time, but usually, one needs to meet several objectives. Usually, there is one optimal solution, but heterogeneity may be important for system performance.

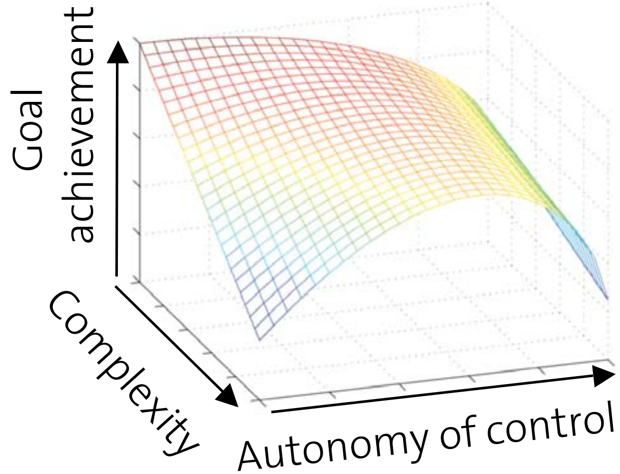



- Evolutionary dead ends: The best solution may be the combination of two bad solutions (i.e. gradual optimization may not work)
- Optimization may destabilize the system
- Example: Utilization of maximum road capacity will eventually cause capacity drops



# Weaknesses of Classical Optimization II

- NP-hardness: Complexity of optimization problem often prevents exact online optimization
- Optimization based on average or past data optimizes for a non-existent situation, i.e. it the applied solution is NOT optimal in reality
- Example: Today's traffic light control
- Often, there is a lack of data to determine model parameters accurately
- Example: Portefolio optimization
- I. Kondor: „The complexity of financial systems exceeds what is knowable"
- Other problems: Information delays or overloads, and inconsistent information
- Problem: What ARE the relevant indicators or control variables?




(Windt, Böse, Philipp, 2006)

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# Thank you for your interest!

# Any Questions?