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From Smart Cities to a Smart World

Prof. Dr. rer. nat. Dirk Helbing, Professor of Computational Social Science
with Anders Johansson, Martin Treiber, Arne Kesting,
Stefan Lämmer, Martin Schönhof, and others

We Can't Anymore Do "Business As Usual"

"Our financial, transportation, and health system are broken."

 Sandy Pentland, MIT Media Lab

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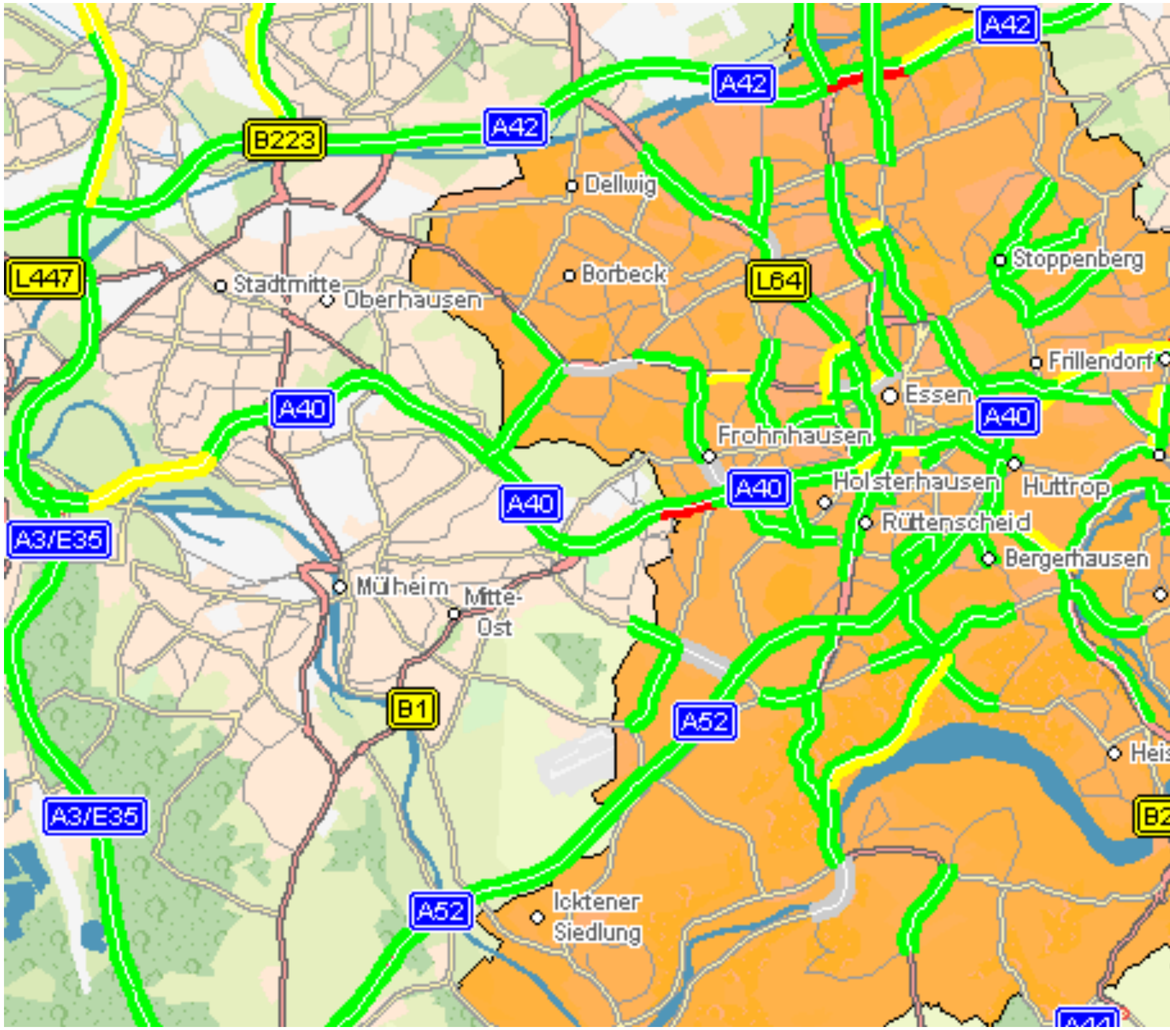
The Noble Goals of Traffic Planning

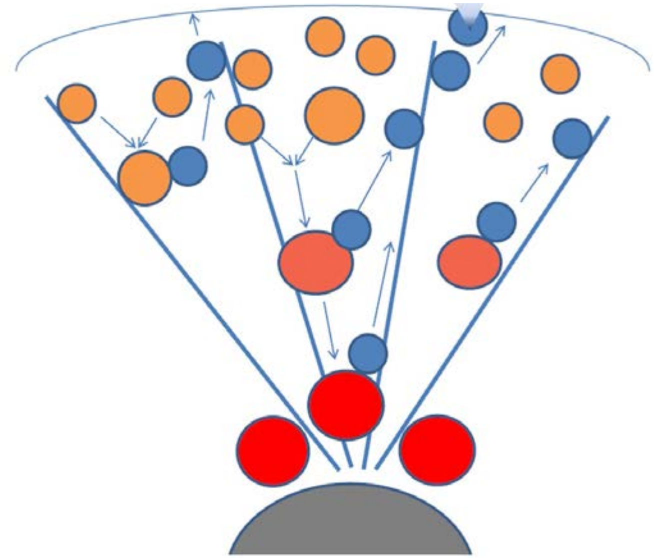
- Better mobility
- Less pollution
- Less noise
- Less traffic

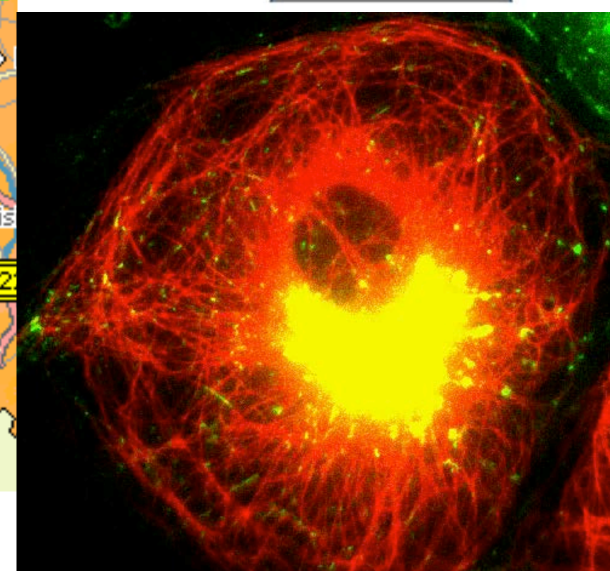
But This Is Often the Reality …

… and This: Urban Gridlock

Flow Towards A Center: Biological Cells Have Figured It Out



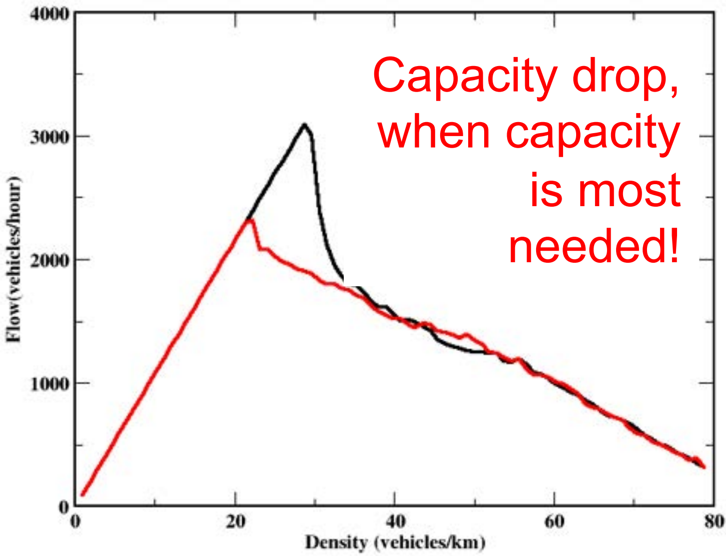




Modeling Freeway Traffic

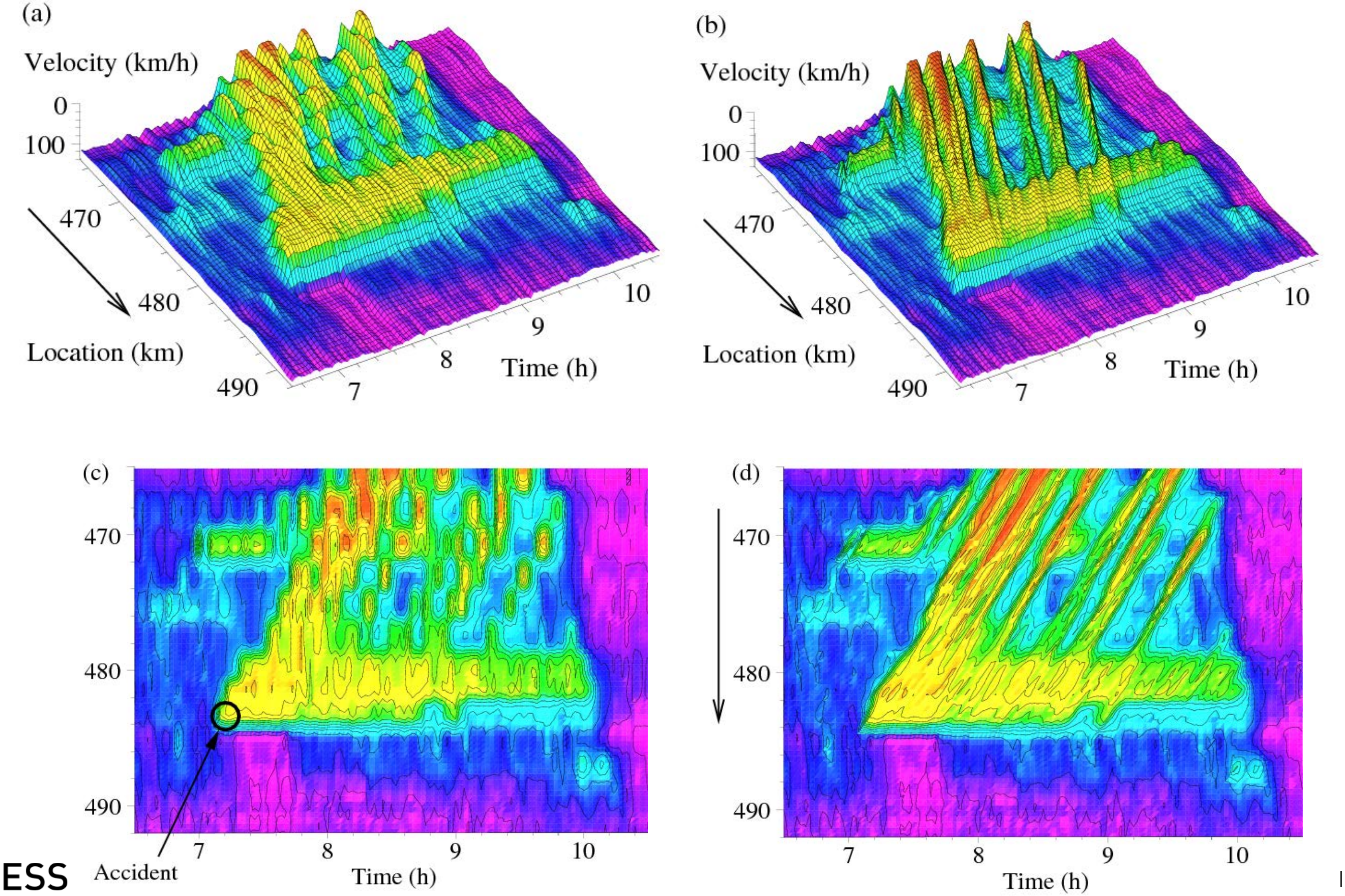
„Phantom Traffic Jams“

Thanks to Yuki Sugiyama

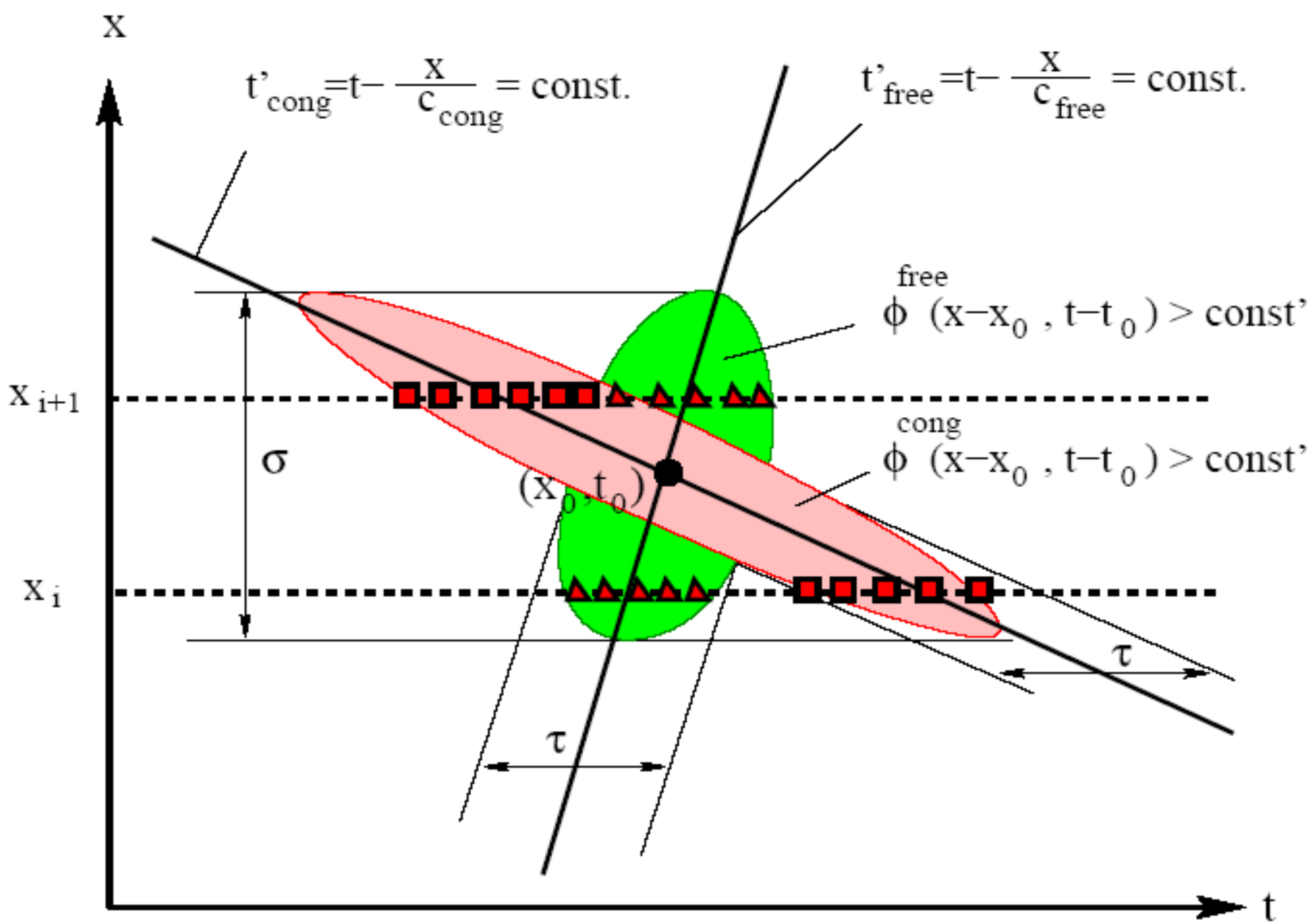


At high densities, free traffic flow is unstable: Despite best efforts, drivers fail to maintain speed

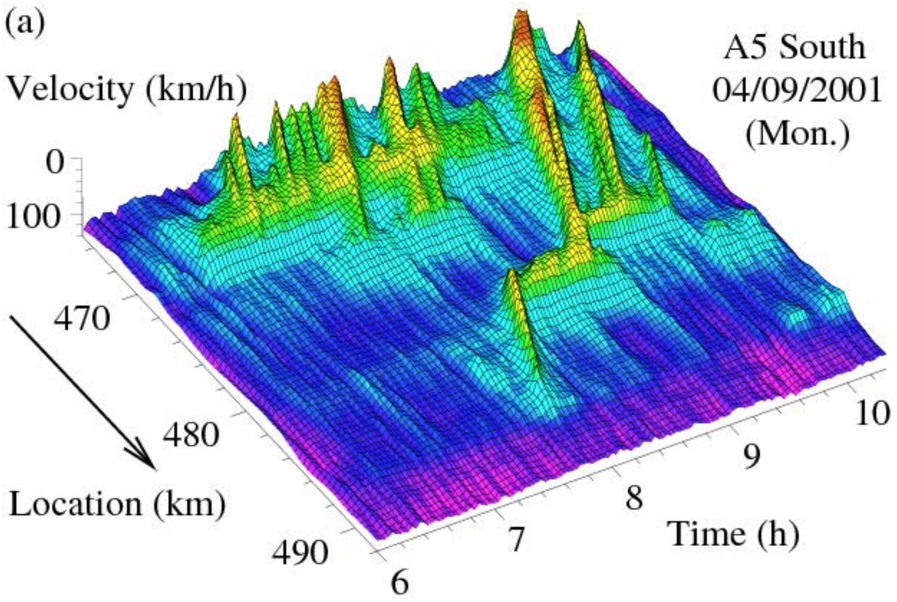
How to Analyze the Cross-Sectional Traffic Data

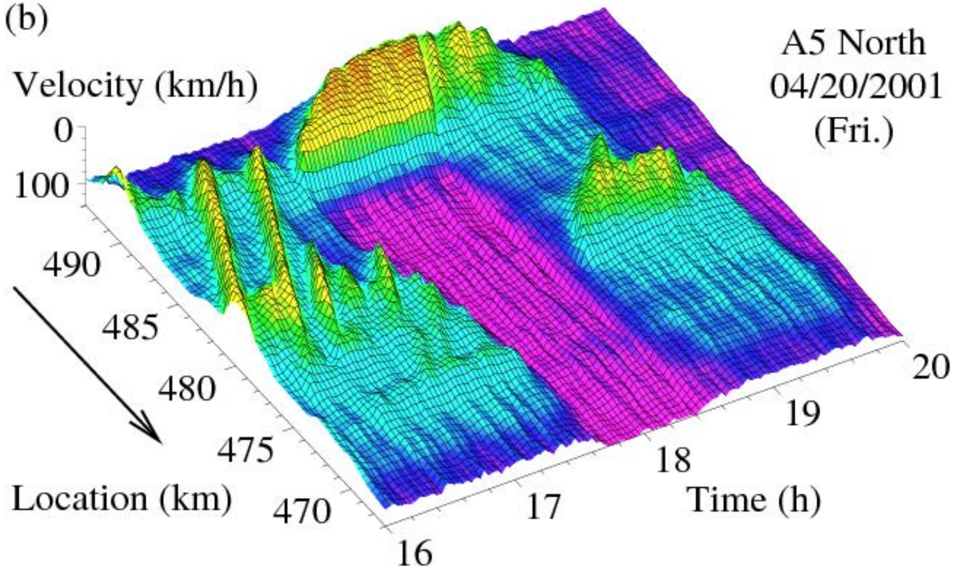


How the Adaptive Smoothing Method Works

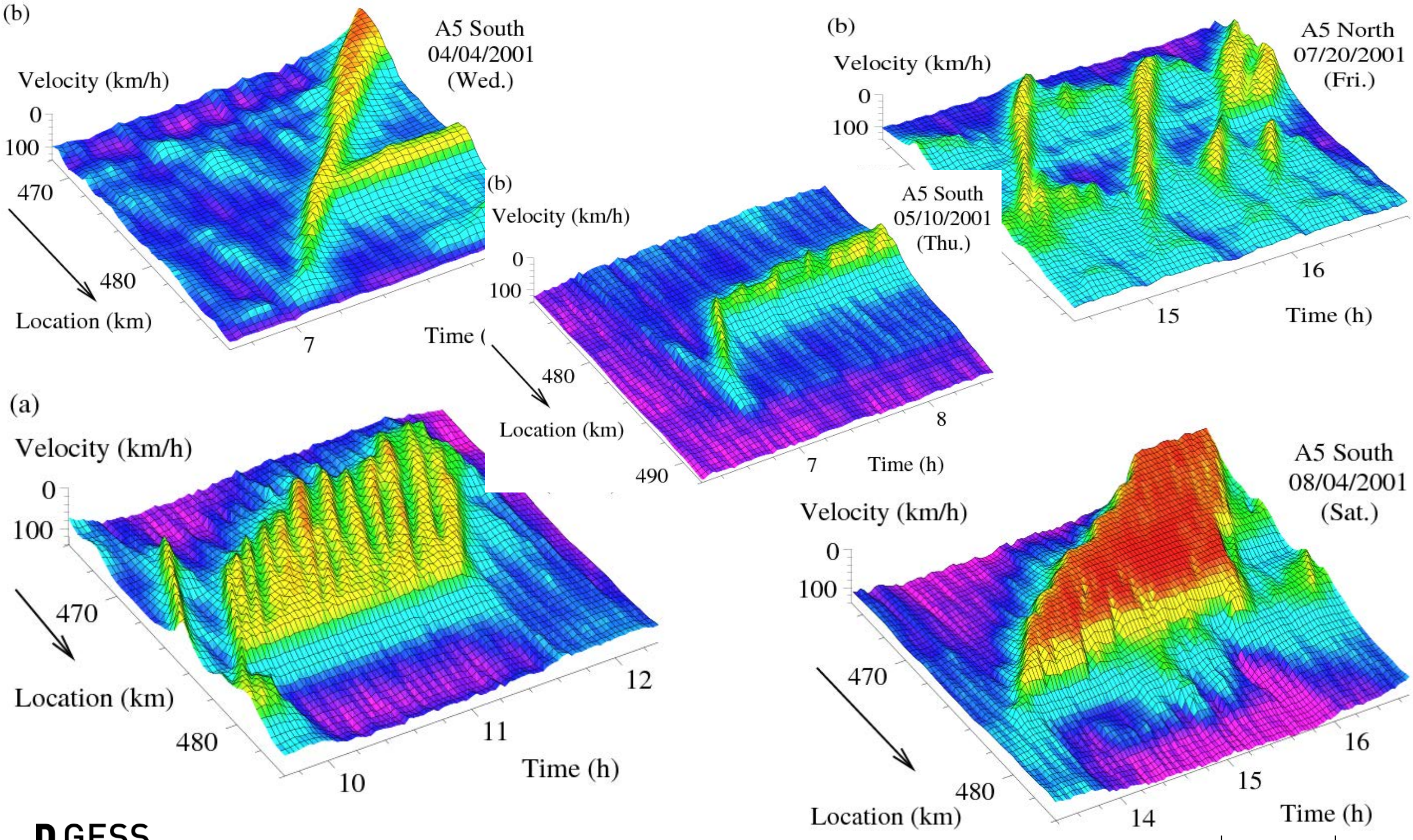


Complex Congestion Patterns

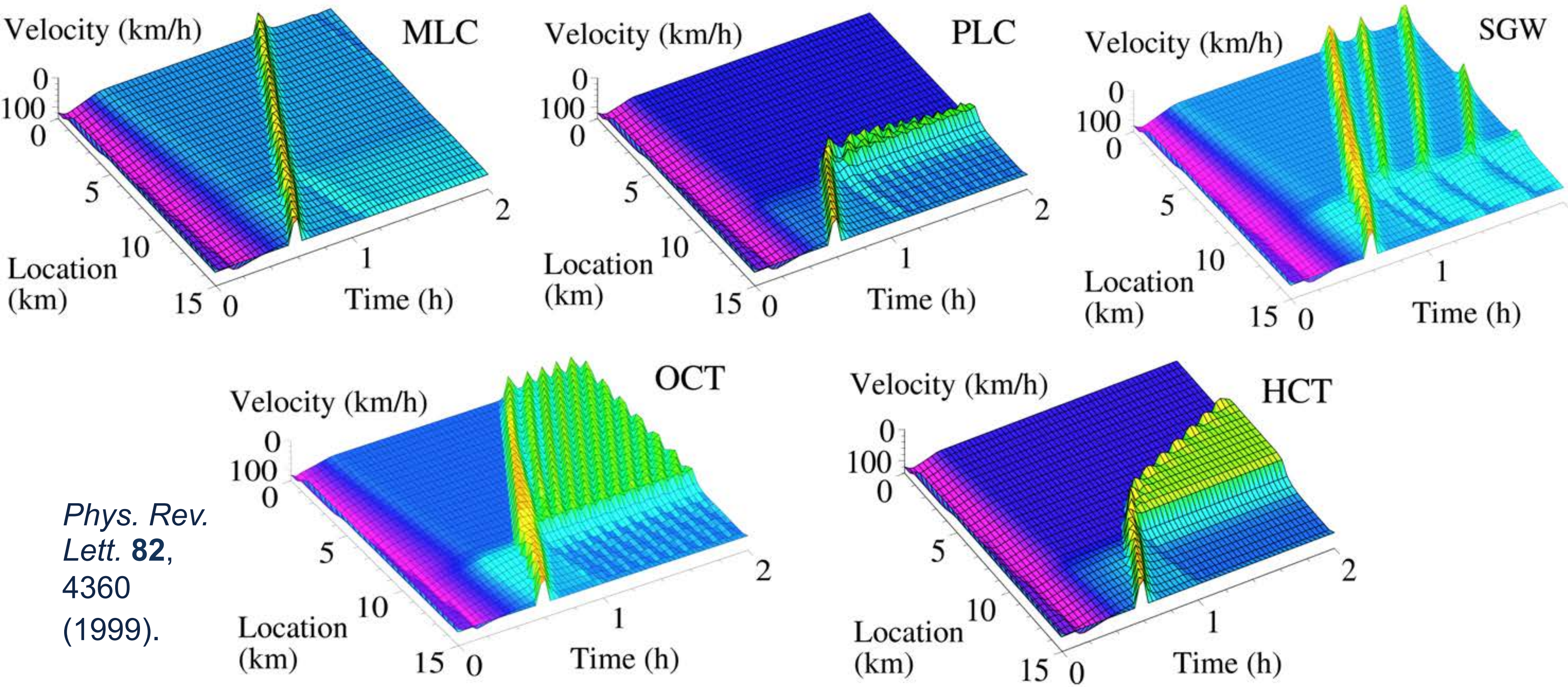




Surprising Variety of Congestion Patterns



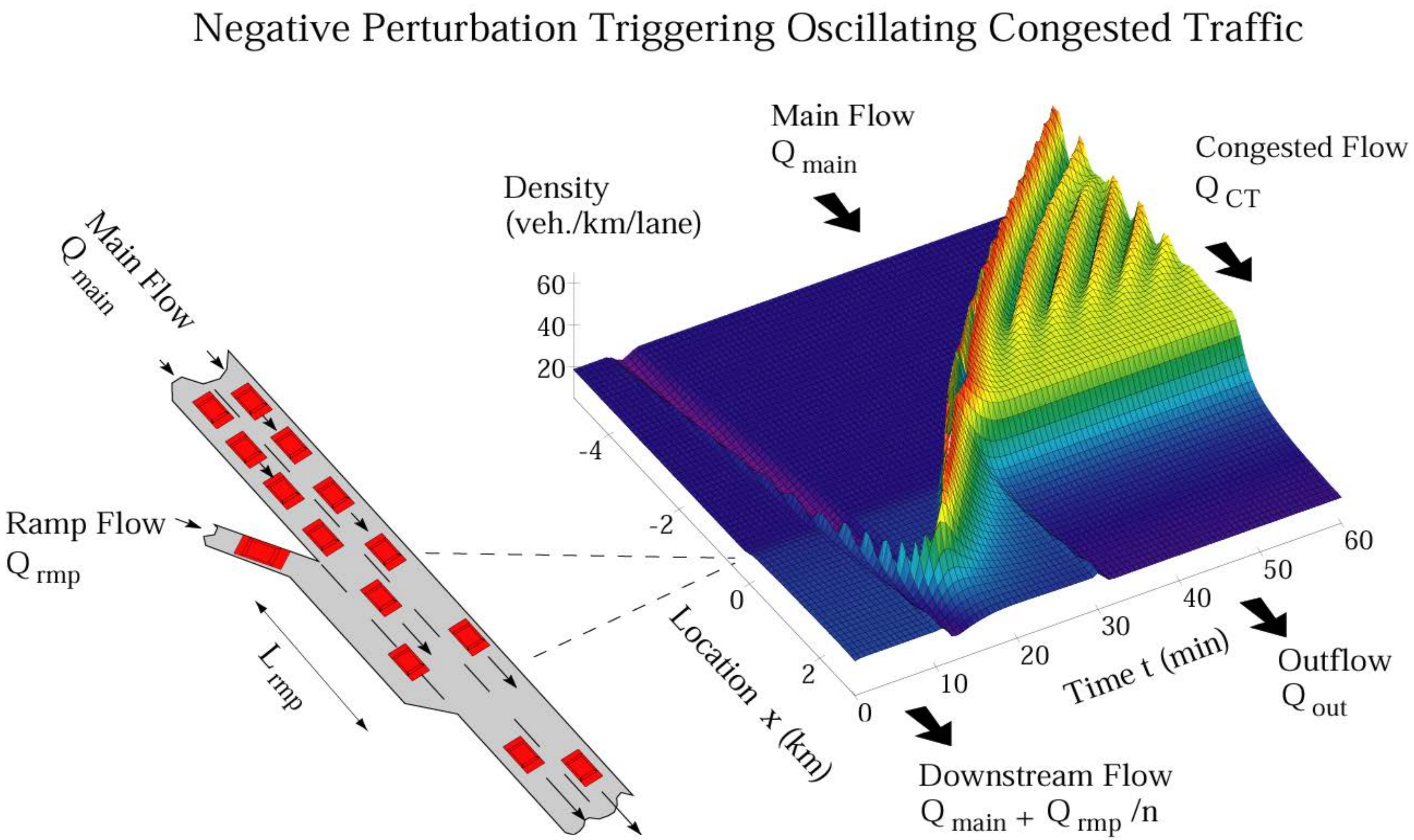
Congested Traffic States Simulated with a Macroscopic Traffic Model



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

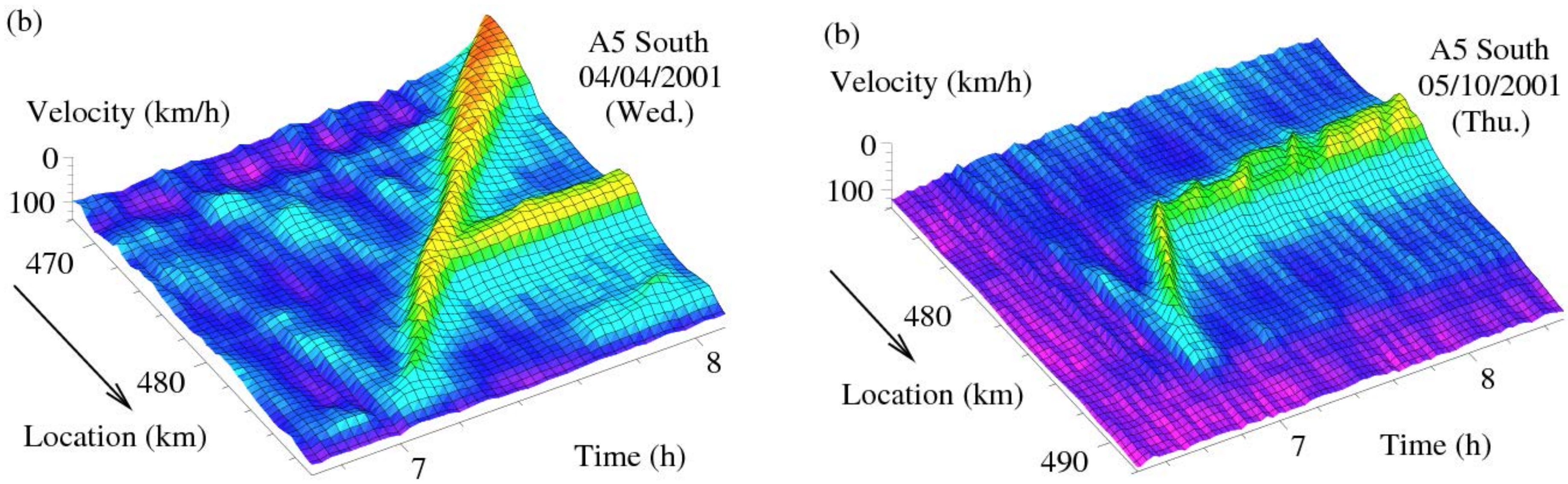
Similar congested traffic states are found for several other traffic models, including “microscopic” car-following models.

Breakdown of Traffic due to a Supercritical Reduction of Traffic Flow

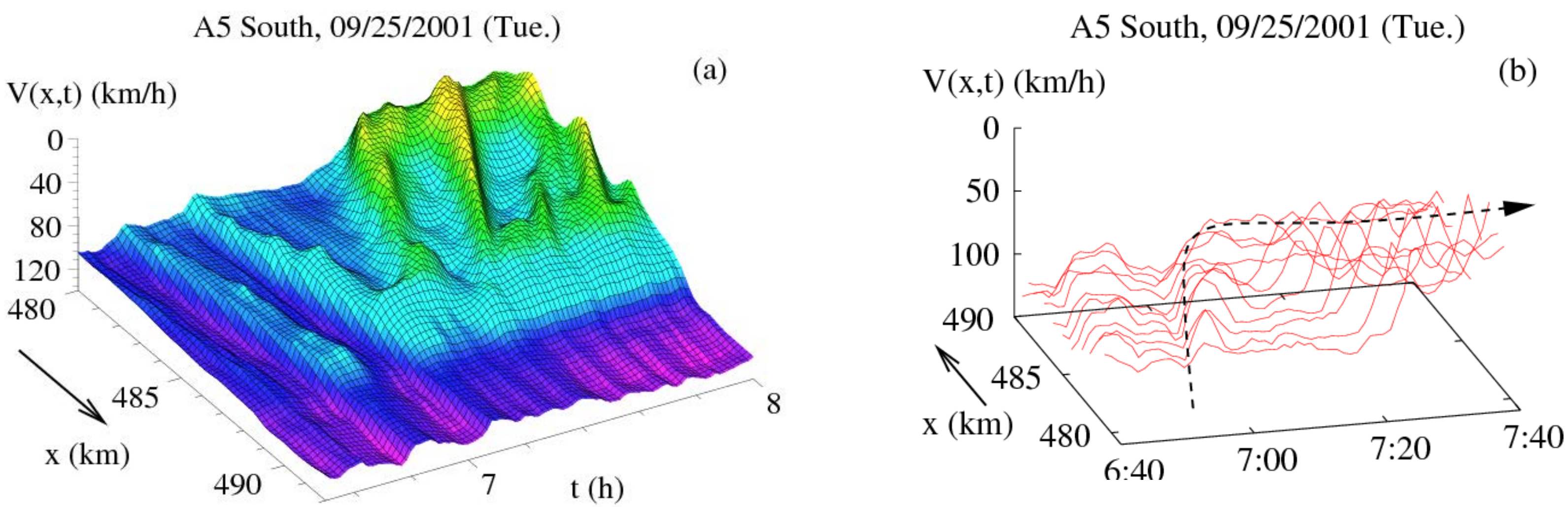


Perturbing traffic flows and, paradoxically, even *decreasing* them may sometimes cause congestion.

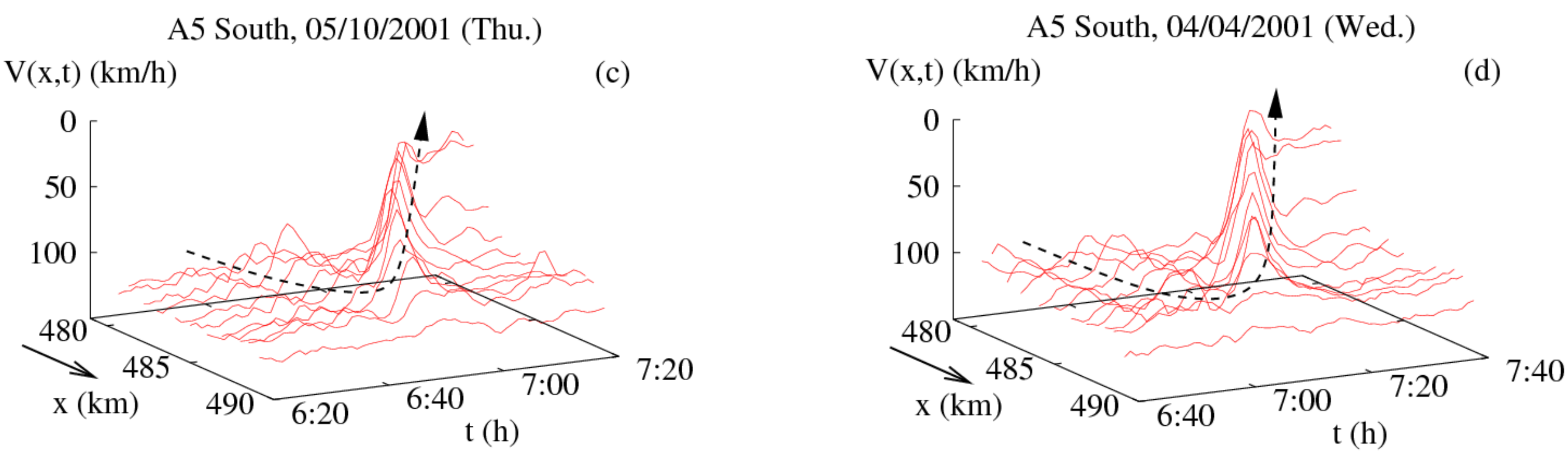
Examples of the “Boomerang Effect”



Transitions from Free to Congested Traffic

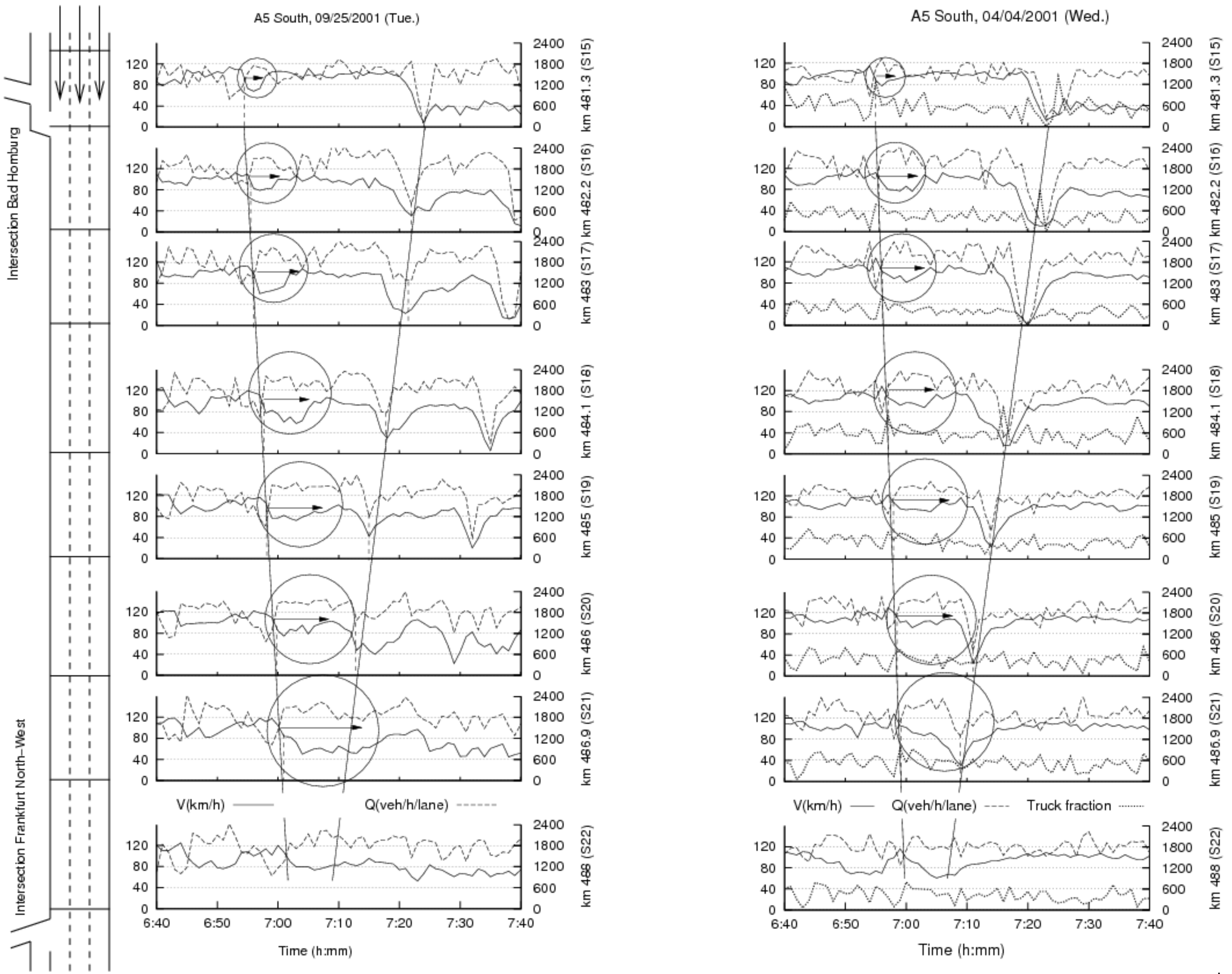


The underlying dynamics of this transition is a “boomerang effect”



The boomerang effect was observed in 18 out of 245 cases of traffic breakdowns.

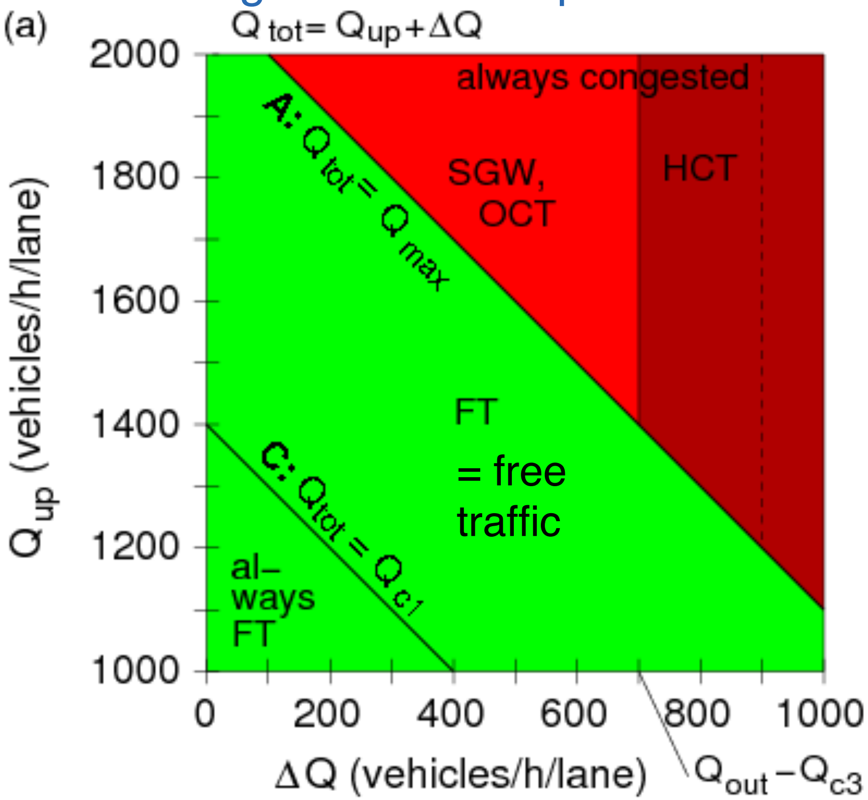
Boomerang Effects Are due to Overtaking Trucks



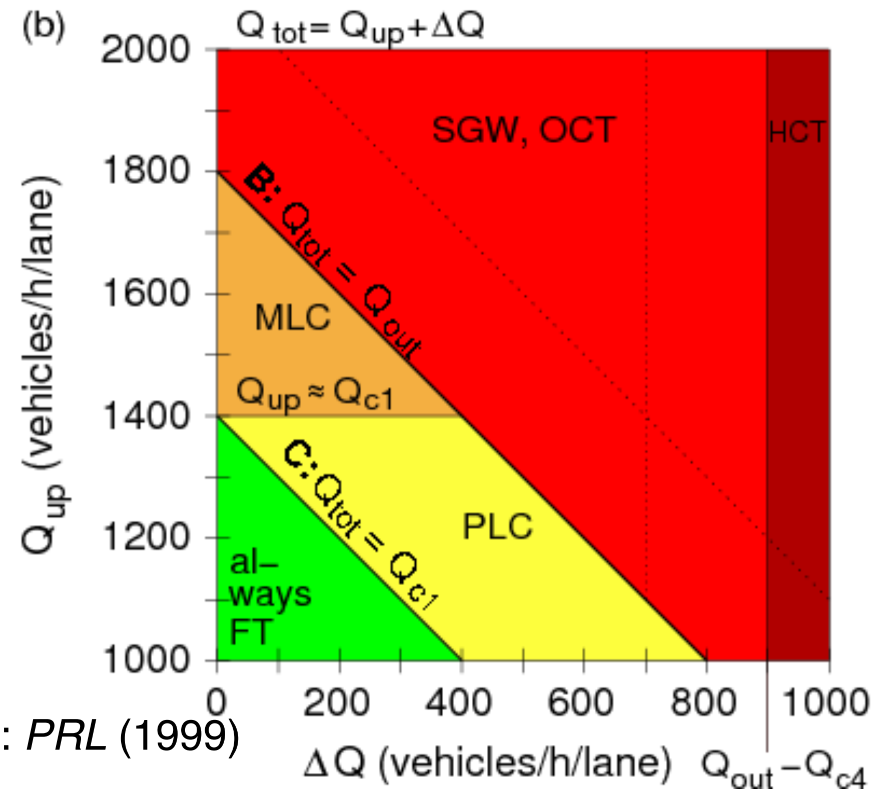
Phase Diagram of Congested Traffic States

Phase Diagram of Traffic States and Universality Classes

Phase diagram for small perturbations

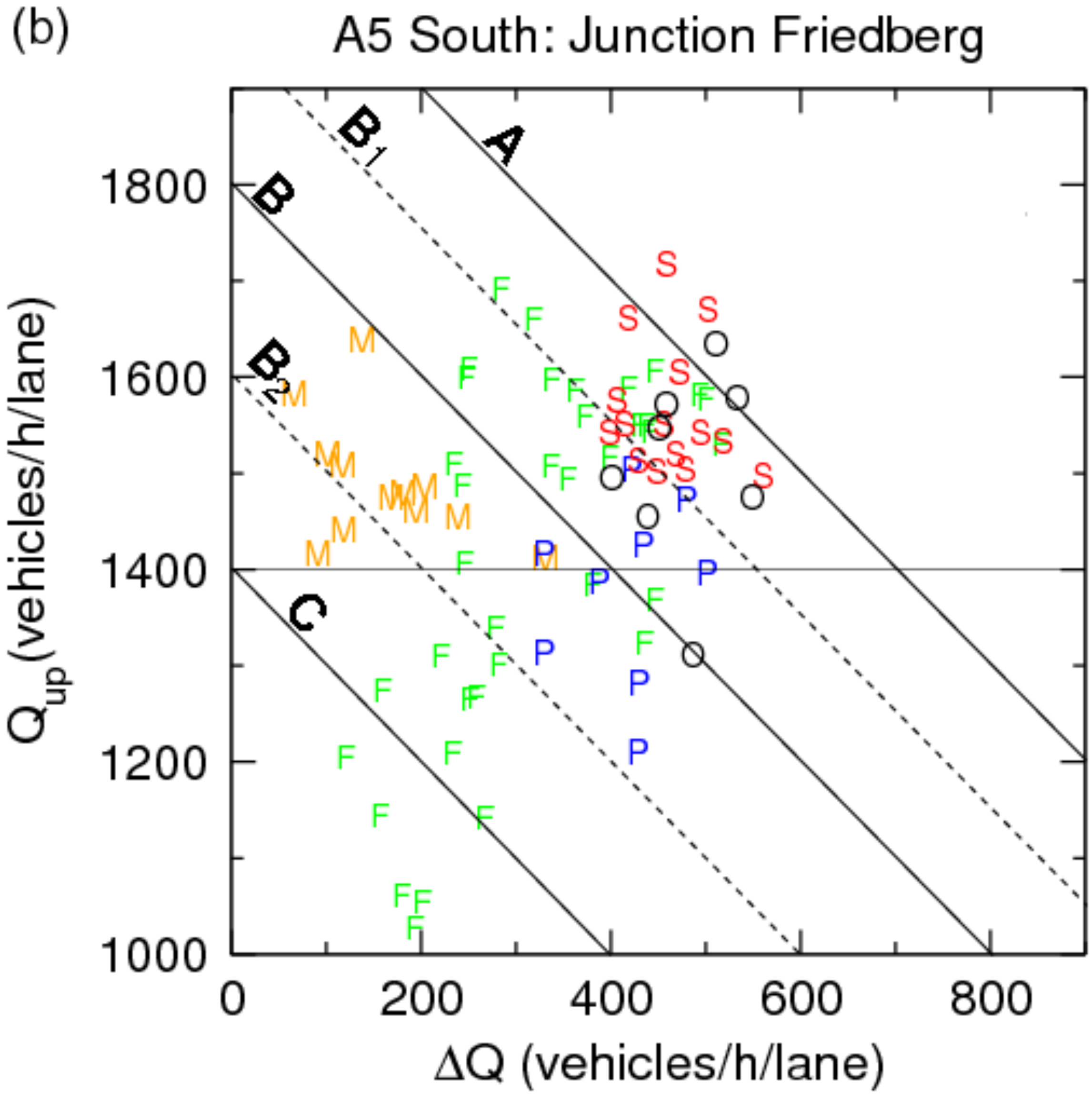


for large perturbations

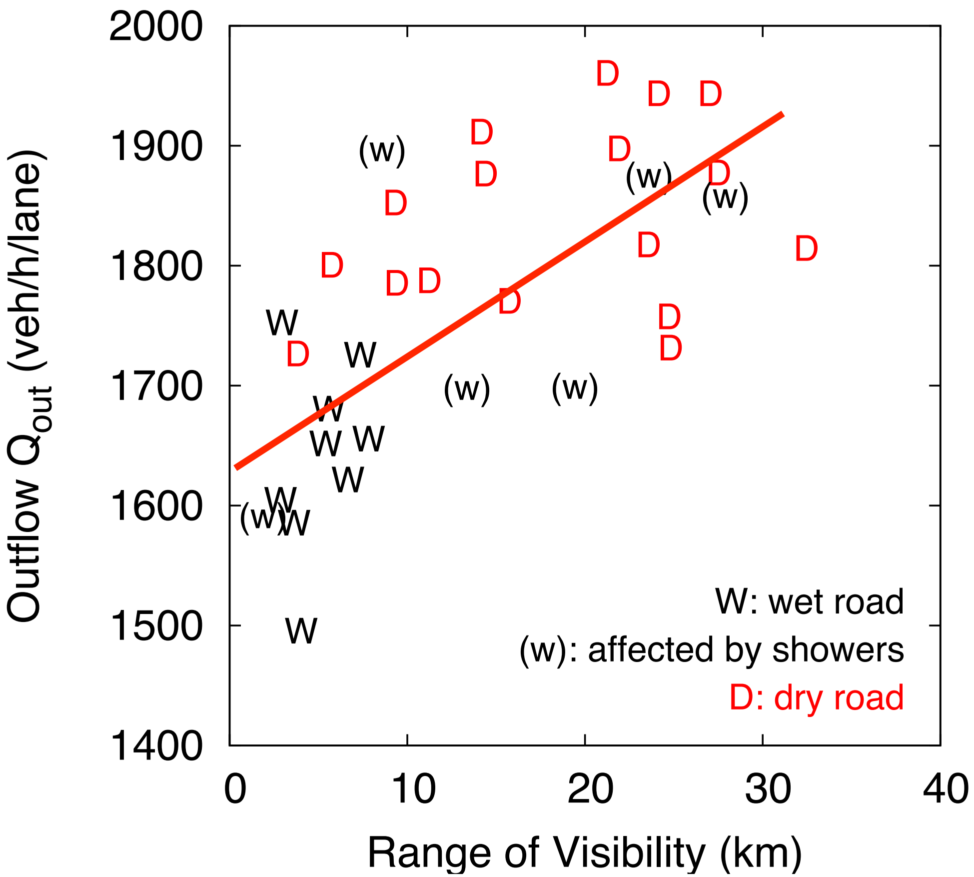


After: *PRL* (1999)

Empirical Phase Diagram

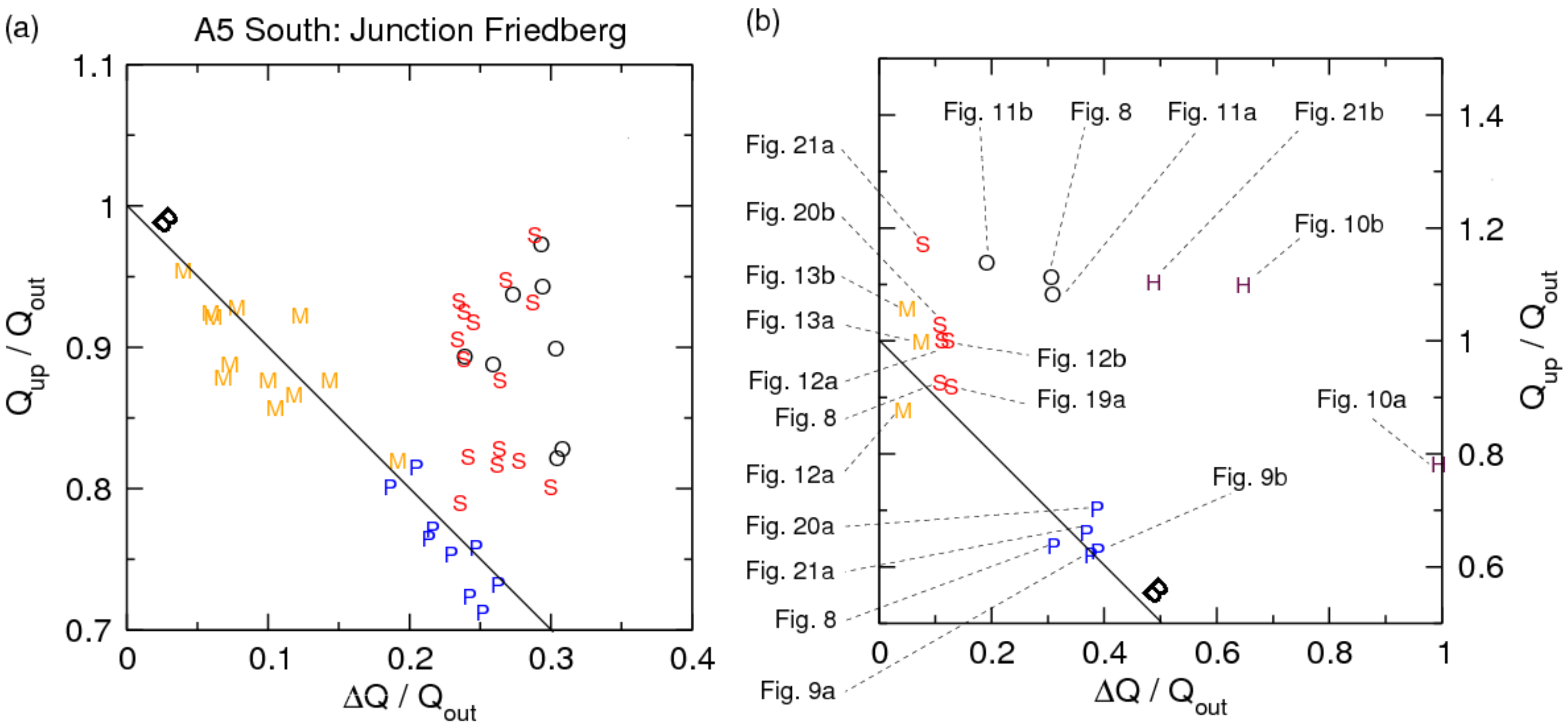


The Outflow Depends on the Weather Conditions

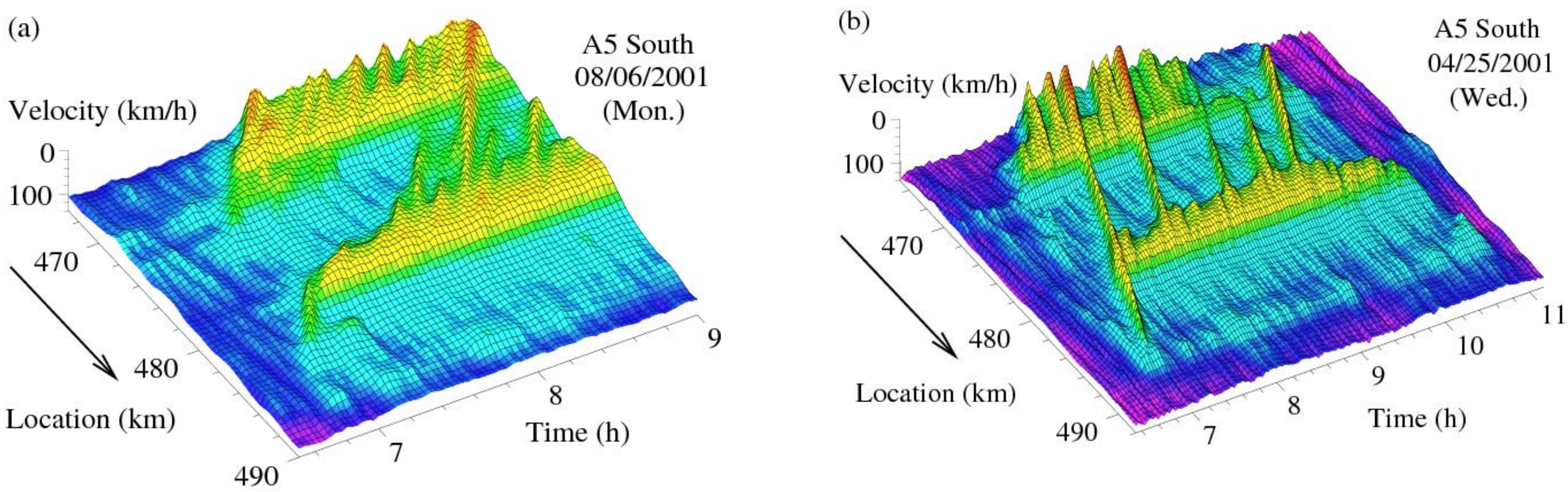


Empirical Phase Diagram for Scaled Flows

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

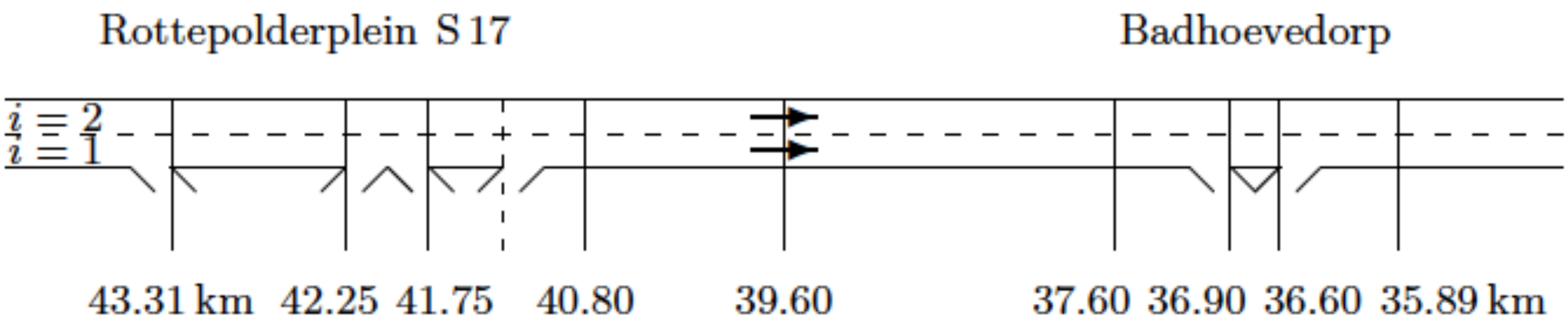


“General Pattern” and “Pinch Effect”

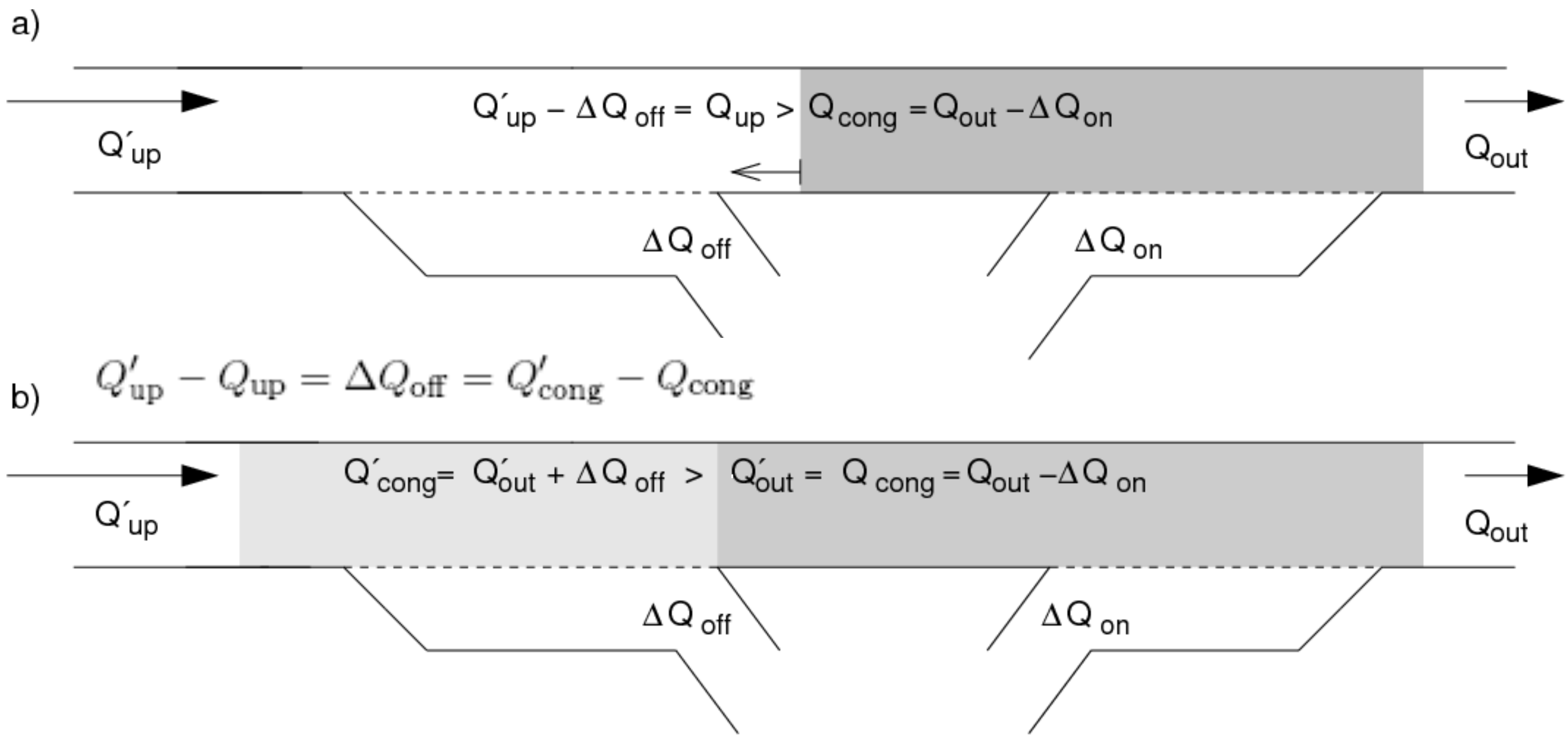


According to Boris Kerner, in the “generalized pattern”, synchronized traffic upstream of a bottleneck breads wide moving jams based on the “pinch effect”. That is, upstream of a section with “synchronized” congested traffic close to a bottleneck, a so-called “pinch region” gives spontaneously birth to narrow vehicle clusters. These perturbations should be growing while traveling further upstream. Eventually, wide moving jams form by the merging or disappearance of narrow jams. Once formed, wide jams suppress the occurrence of new narrow jams in between.

Typical Freeway Design



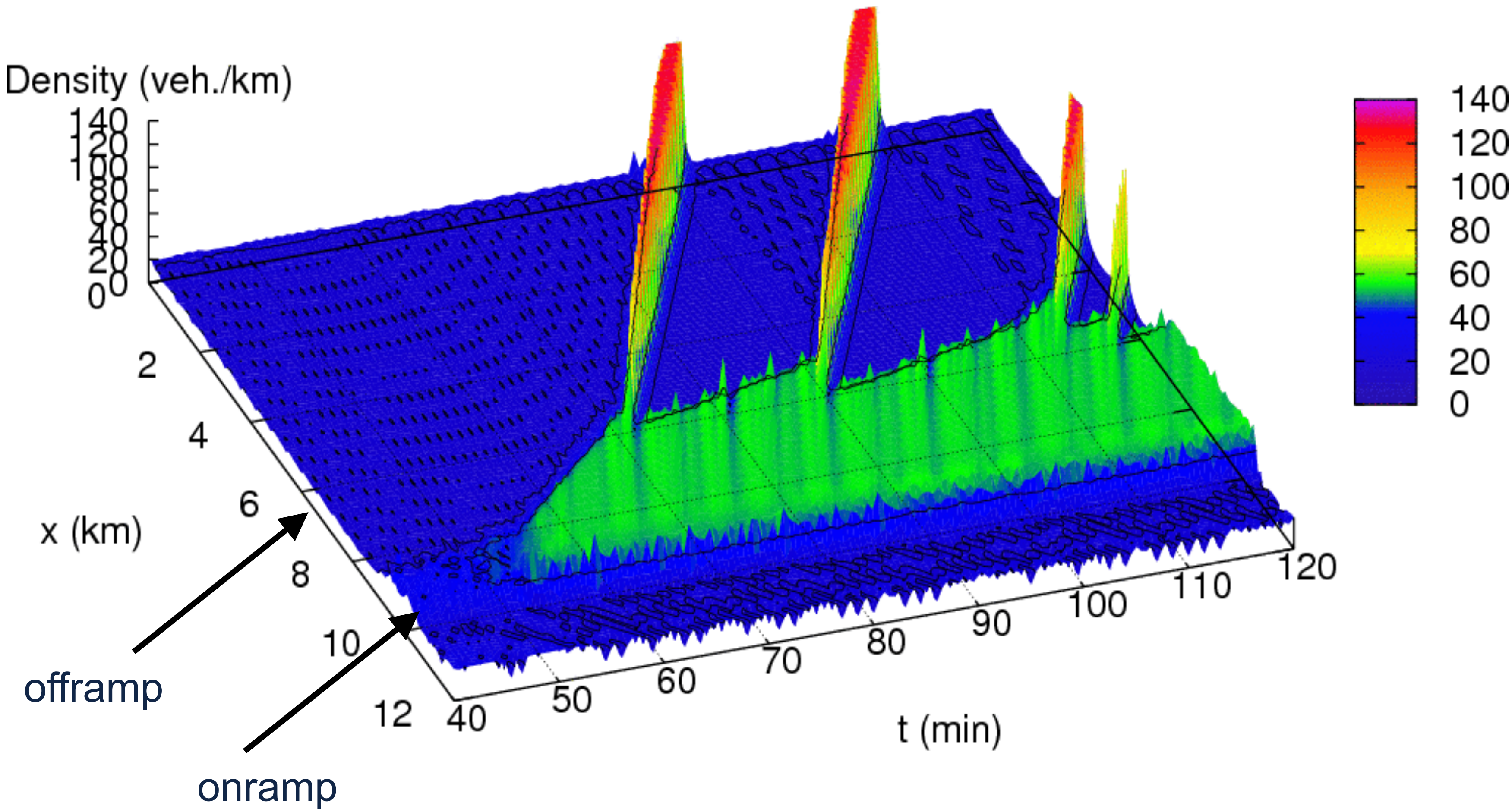
(Intermittent) Activation of an Off-Ramp Bottleneck



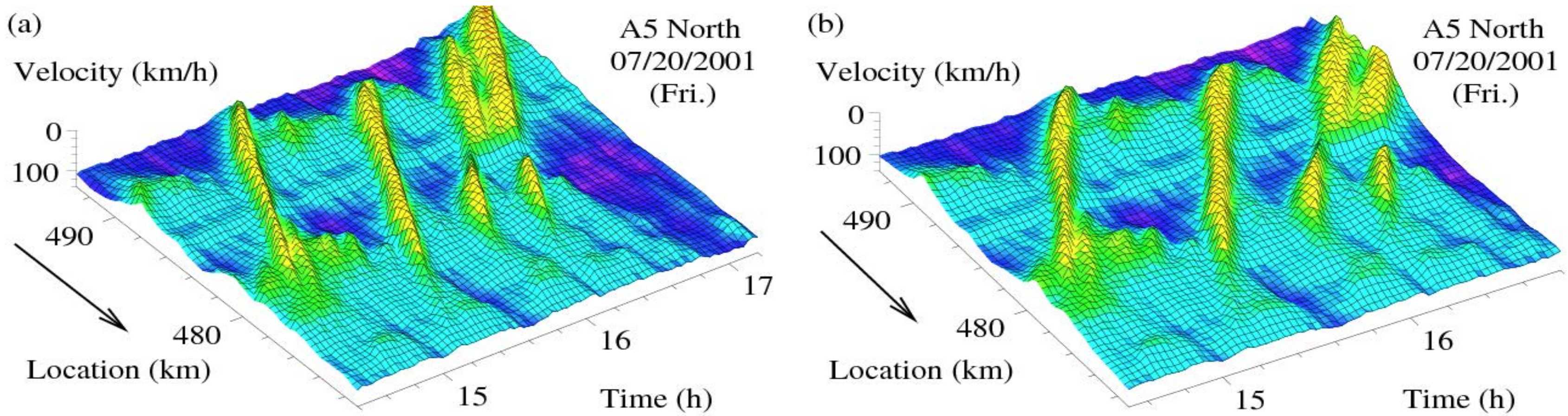
$$\Delta Q = \max(\Delta Q_{\rm on} - \Delta Q_{\rm off}, 0) = \max\left(\frac{Q_{\rm rmp}}{n} - \frac{Q'_{\rm rmp}}{n'}, 0\right) \leq \Delta Q_{\rm on}$$

Milder form of congested traffic upstream of off-ramp expected, e.g. OCT or SGW instead of HCT. Looks like the "general pattern" (see next slide).

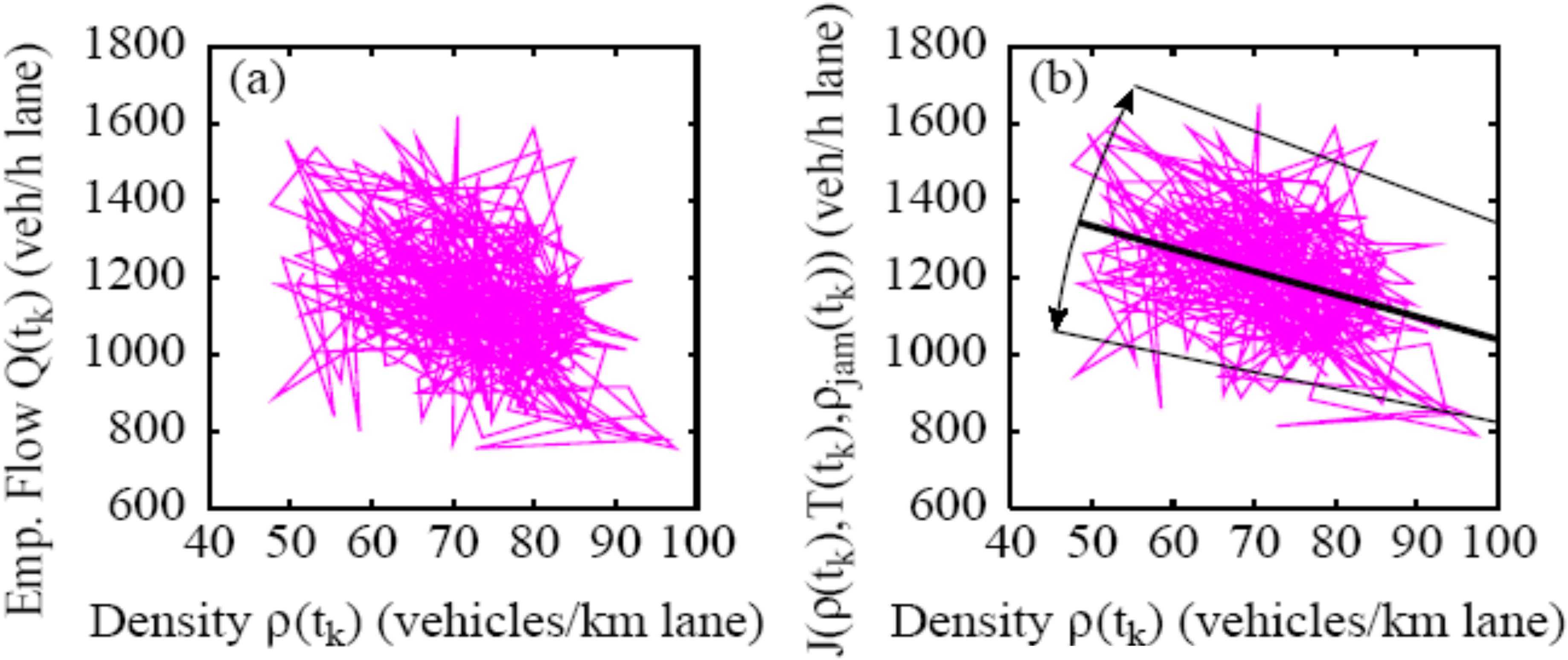
Combination of an Off-Ramp with an On-Ramp



Stop-and-Go Waves Emerging at a Gradient Look Different



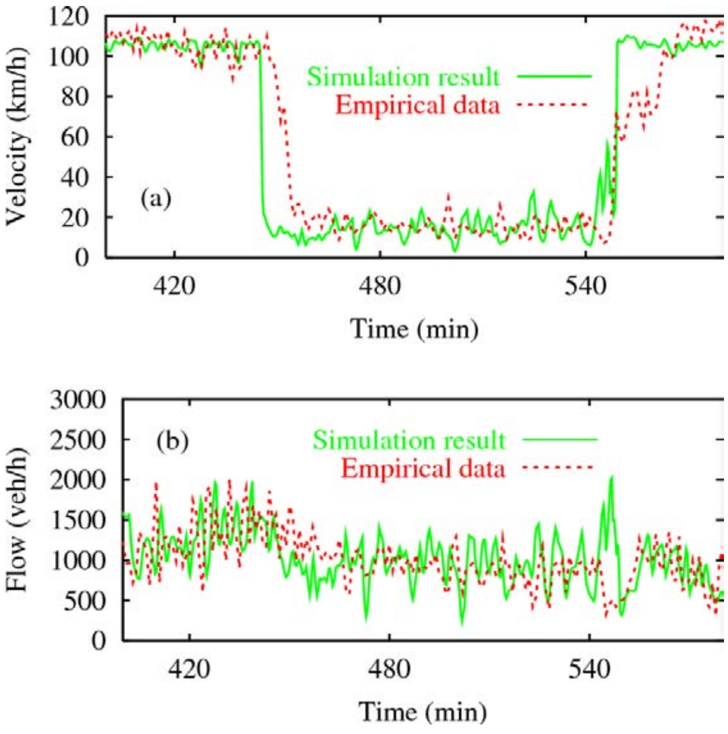
Wide Scattering as Effect of Heterogeneous Traffic



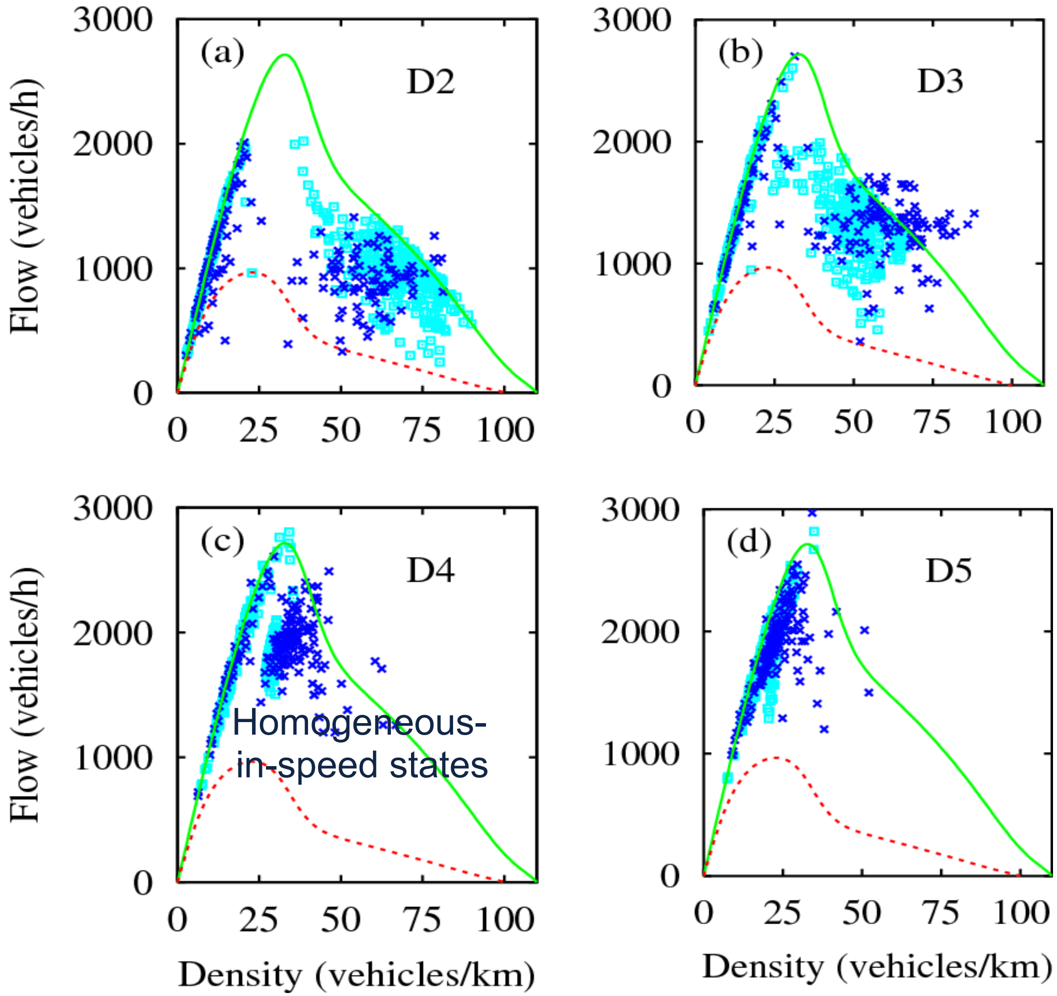
$$Q(t) = \frac{1}{T(t)}\left(1 - \frac{\rho(t)}{\rho_{\text{jam}}(t)}\right)$$

The jam line with variable parameters can explain the observations quantitatively! Scattering and stochasticity do not contradict models with a fundamental diagram, just models with identical driver-vehicle units.

"Synchronized Traffic" Considering Cars+Trucks

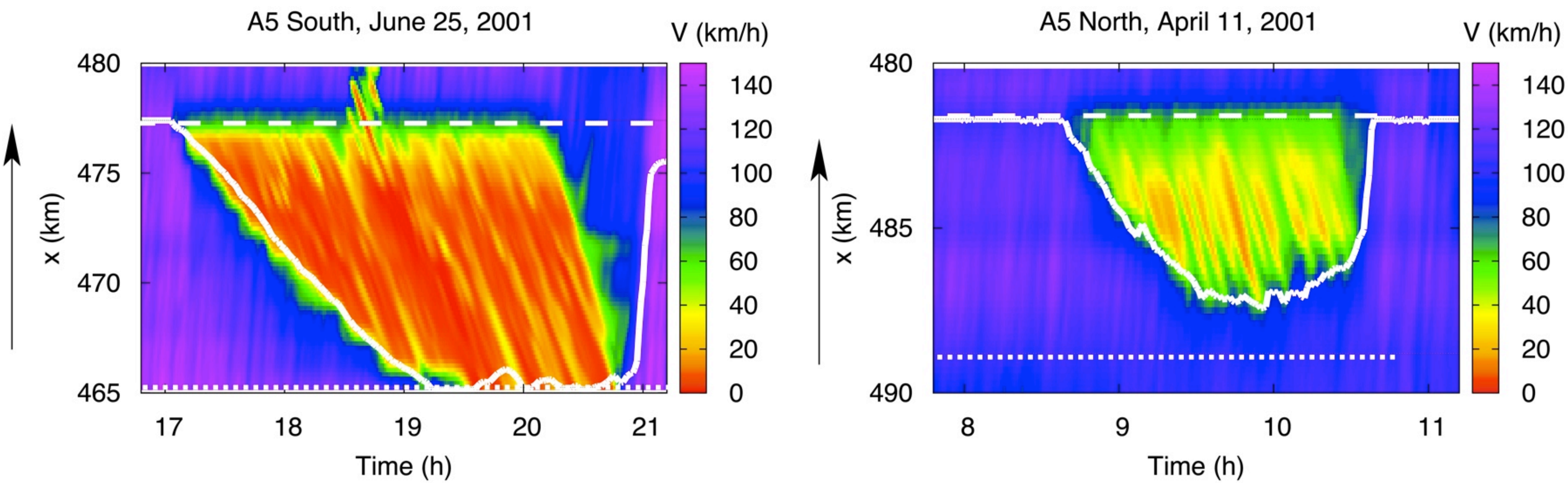


Time series

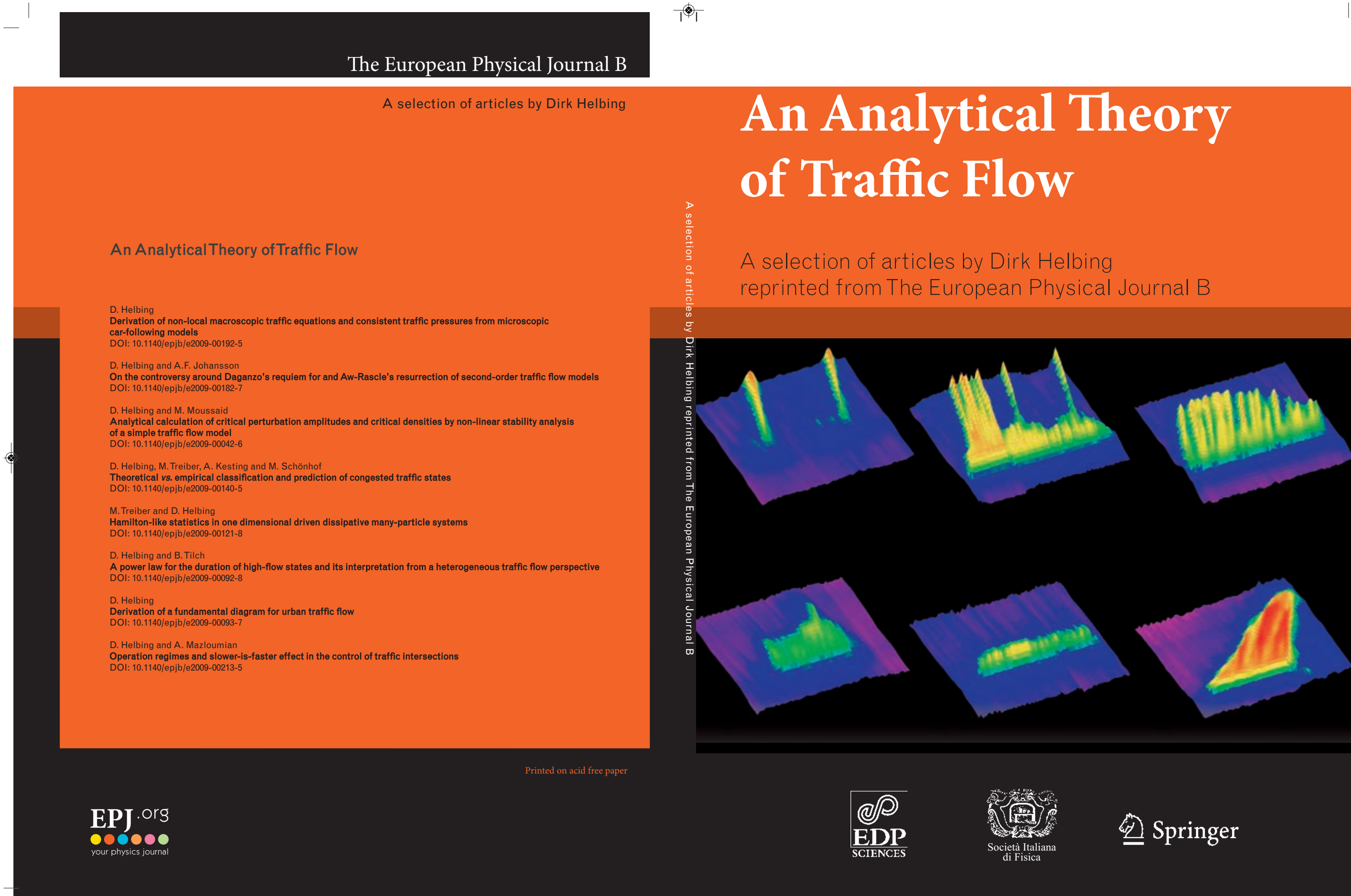


Fundamental diagram

Traffic Congestion is Predictable



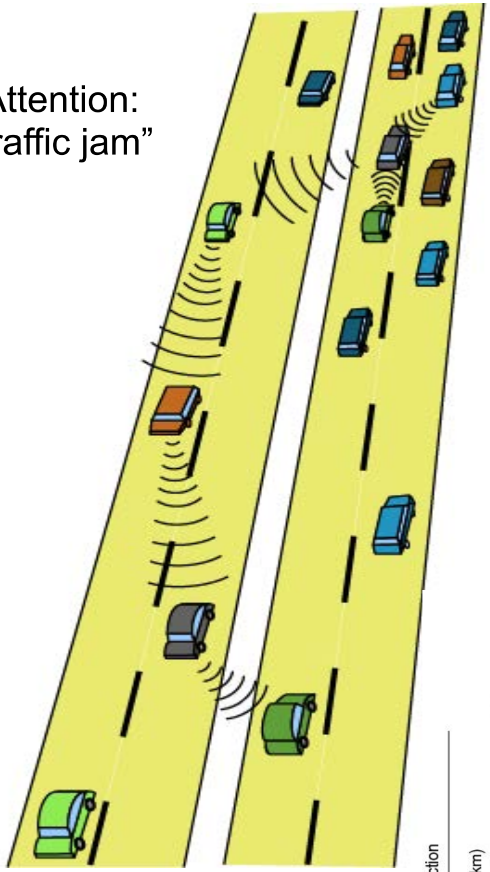
Traffic Physics



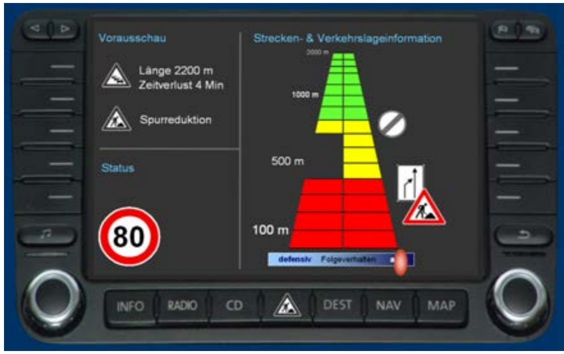
Freeway Traffic Control

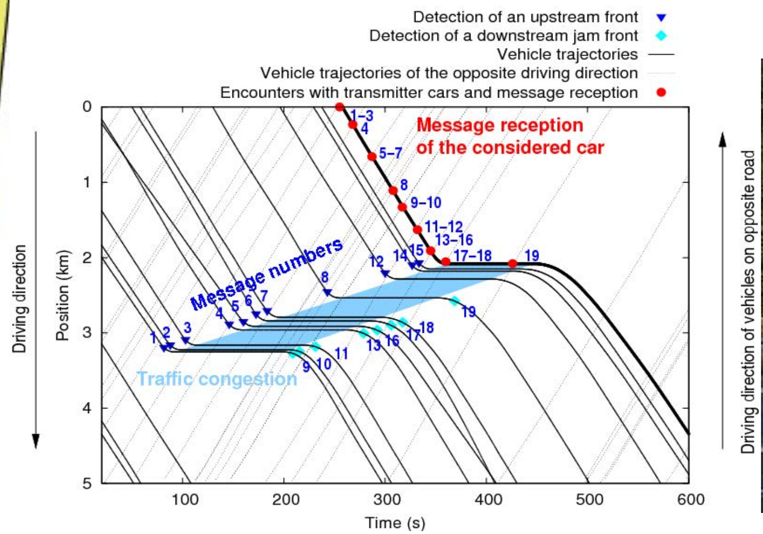
Cooperative Driving Based on Autonomous Vehicle Interactions

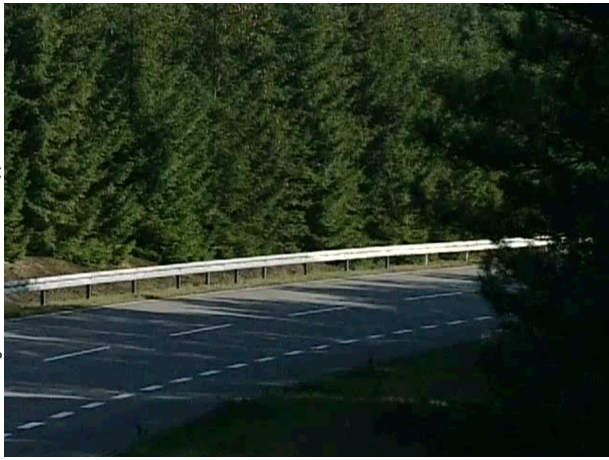
"Attention: Traffic jam"



- 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)

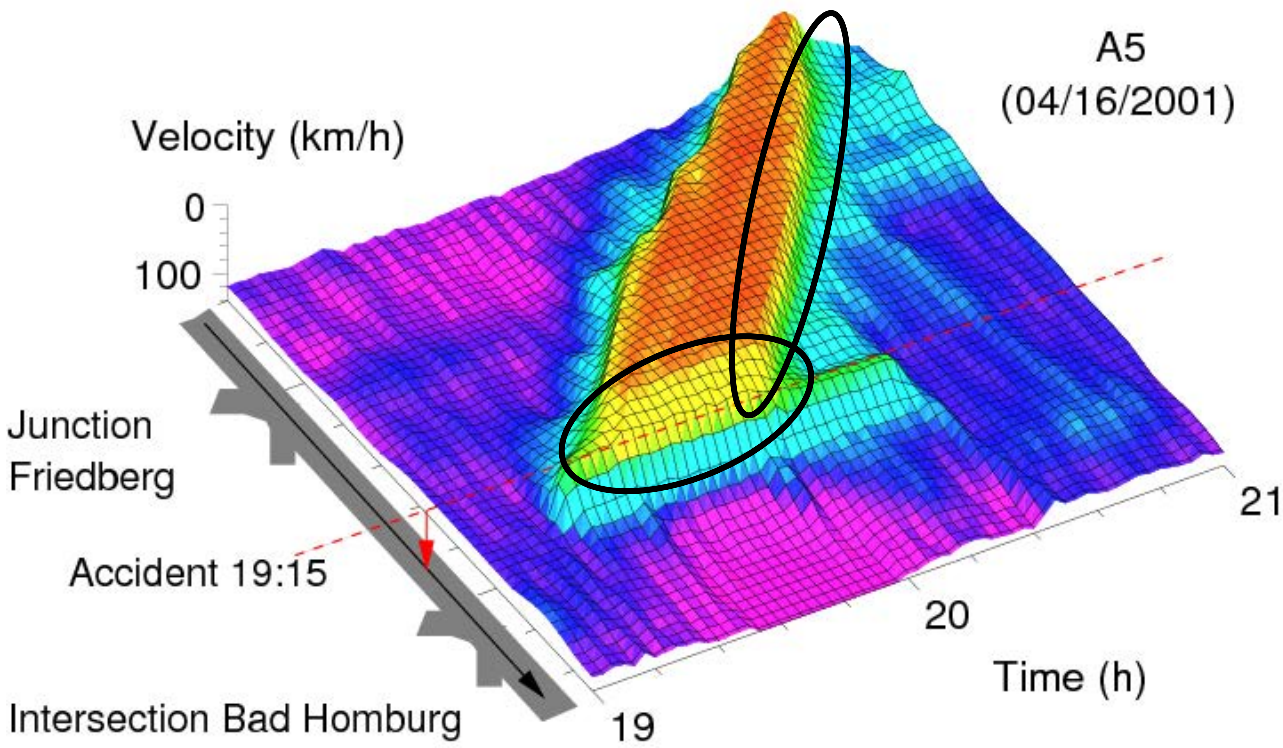






In: *Transportation Research Record* (2007)

How to Detect the Spatiotemporal Dynamics of a Traffic Jam?



Downstream jam fronts

Jam Front Detection – Intervehicle Communication

Inter-Vehicle-Communication (V2V):

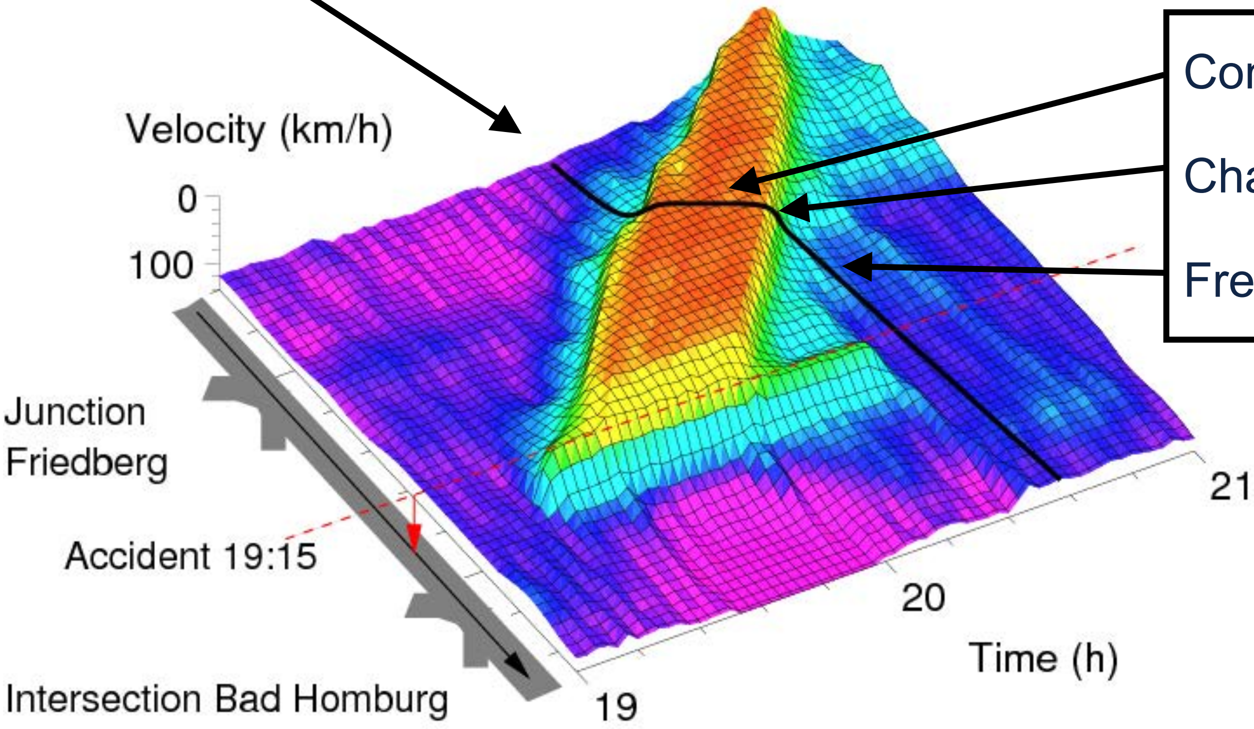
Floating car (ACC)

Message core:

Congested traffic

Change: Position,Time

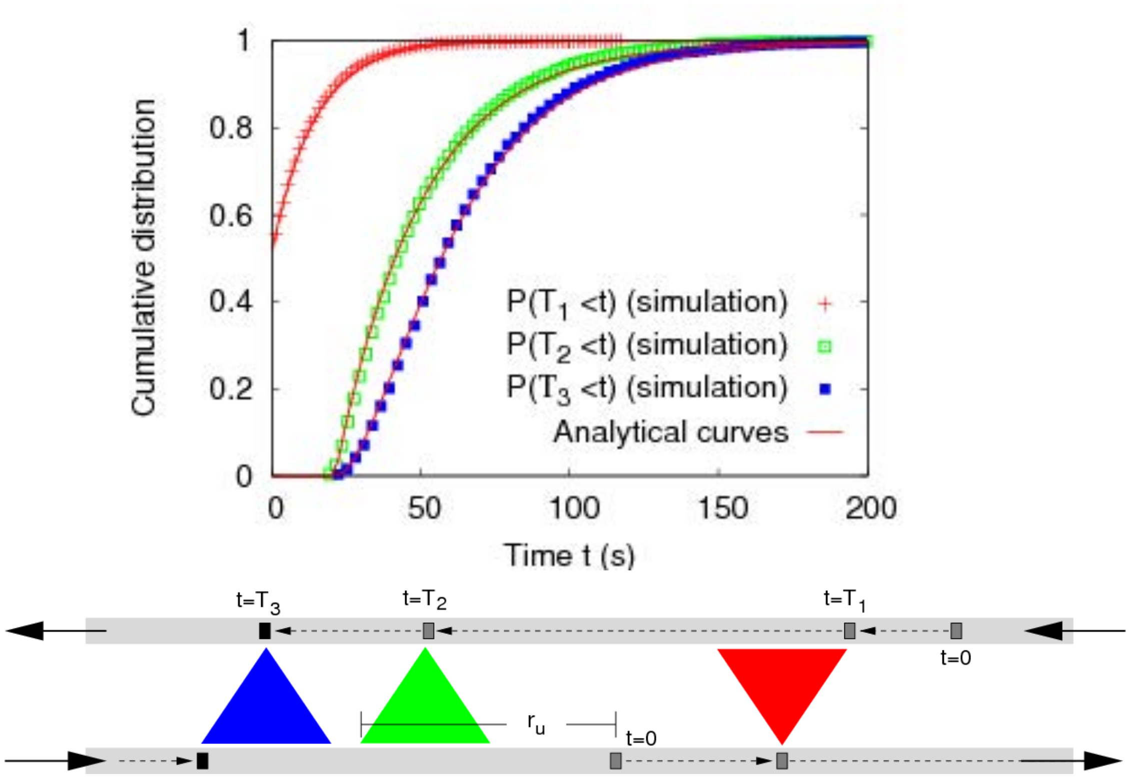
Free traffic



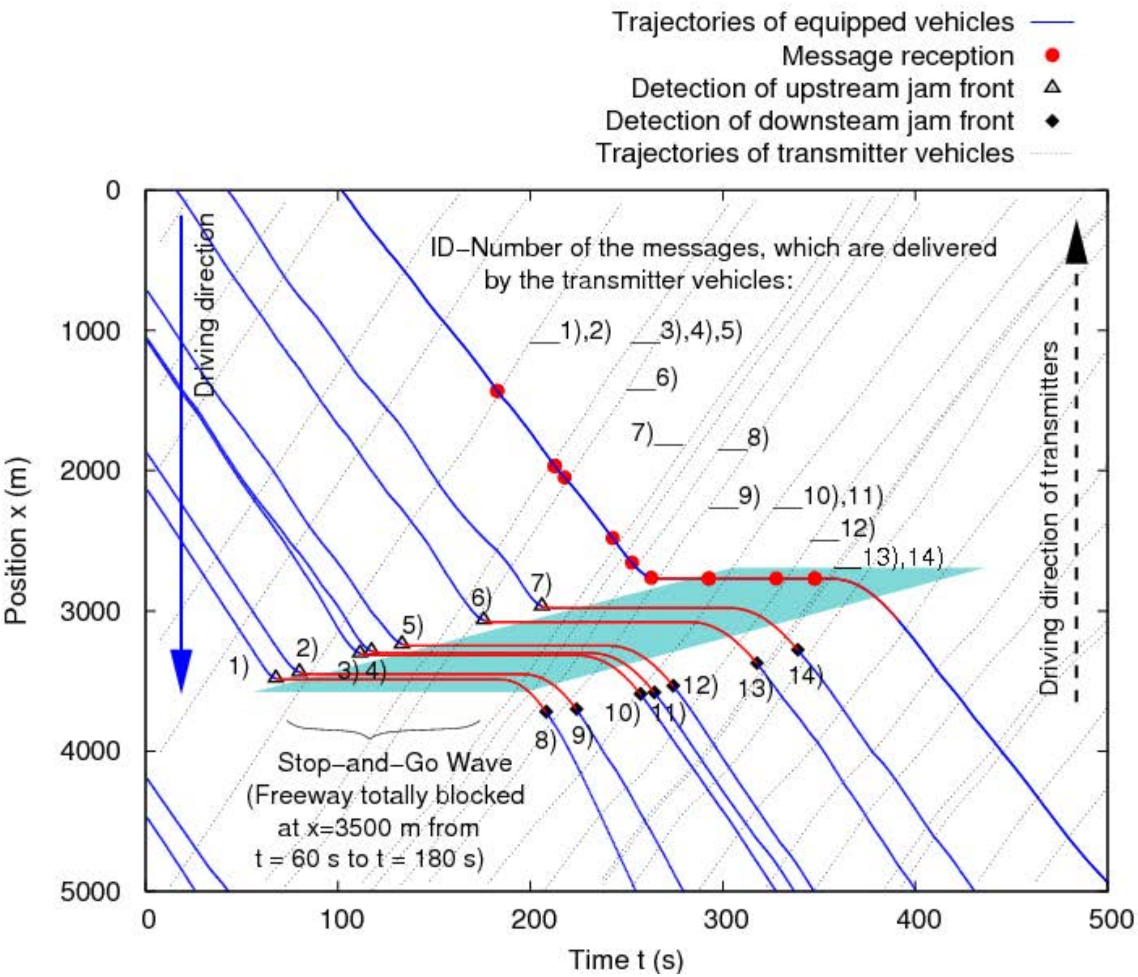
Statistics of Message Transmission

Distance between communicating vehicles exponentially distributed
→ Distributions for T1, T2, and T3,

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

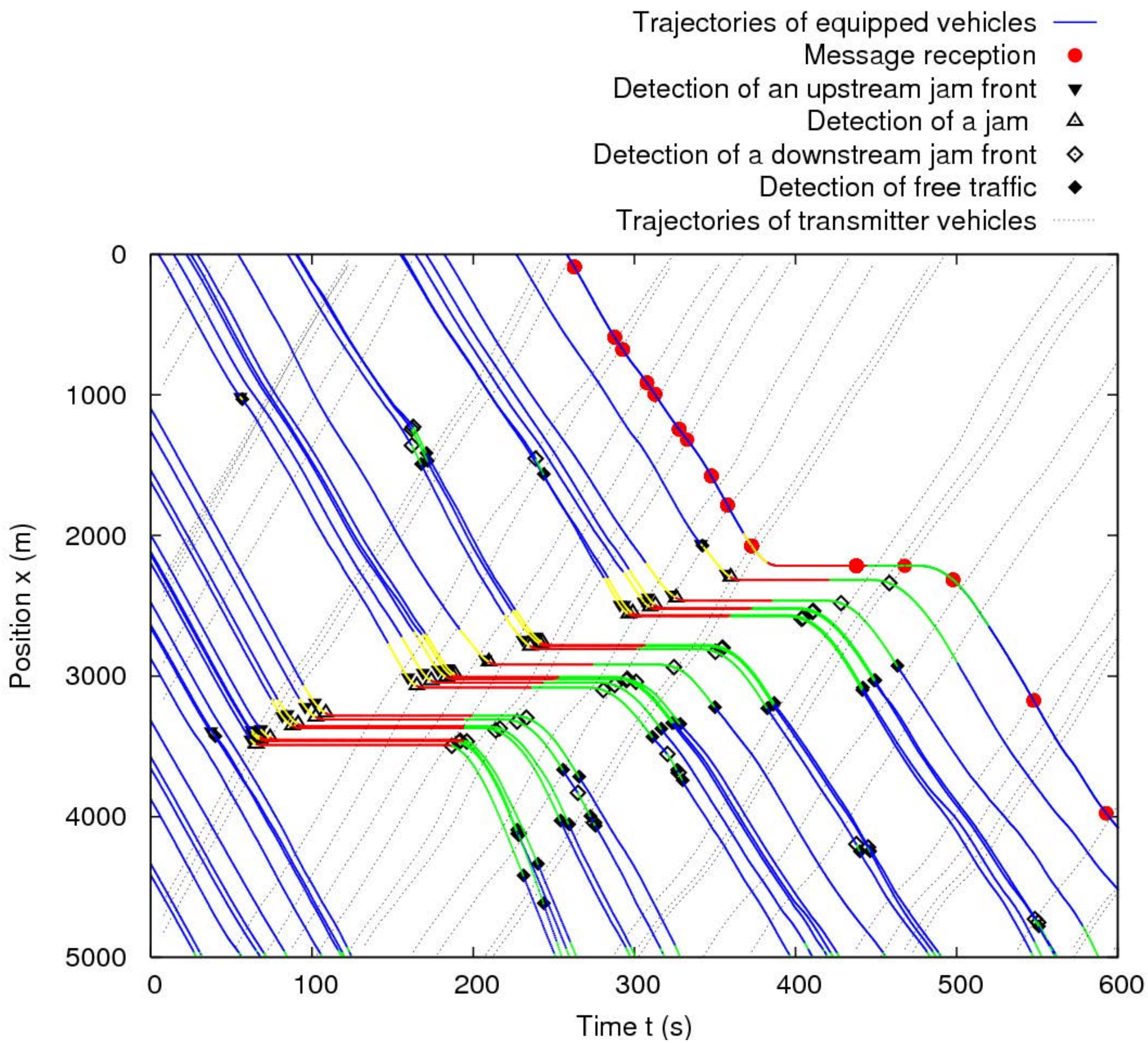


Example: Information about a Stop-and-Go Wave



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

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

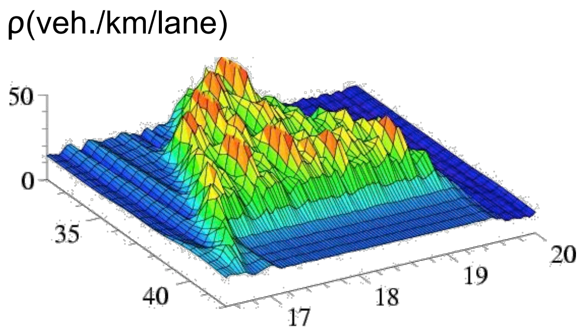
Downstream Bottom of Congestion
Forceful and accurately timed acceleration most important

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

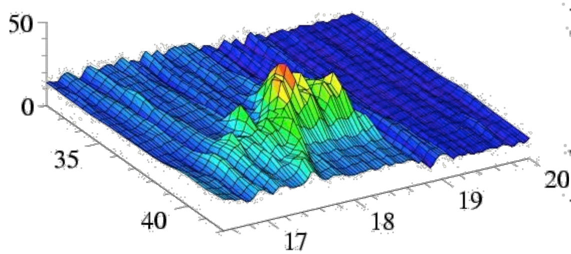
Driving in Bottleneck Section
Increase local capacity by decreasing time gaps
(dyn. homogenization)

Overcoming Congestion by Real-Time Feedback

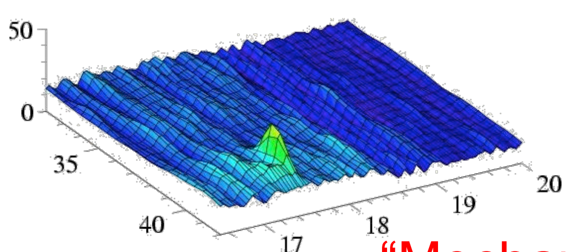
Enhancing Traffic Performance by Adaptive Cruise Control



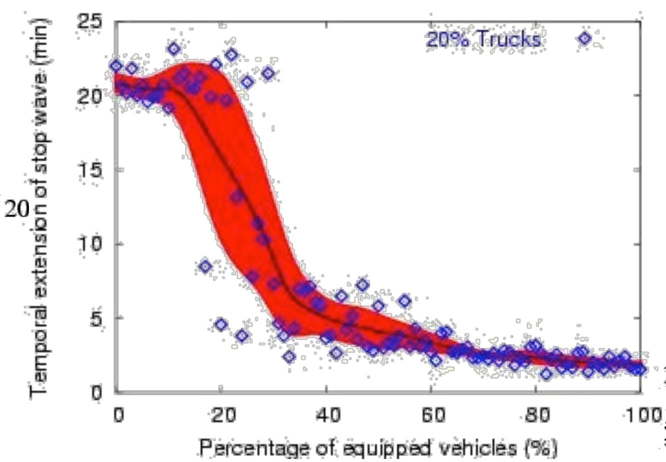
10% Equipped Vehicles

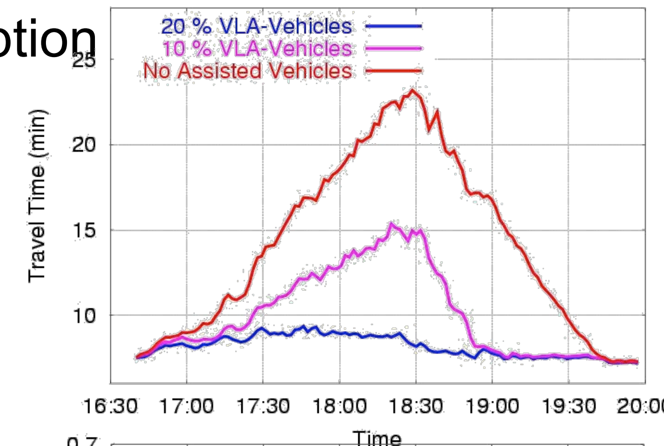


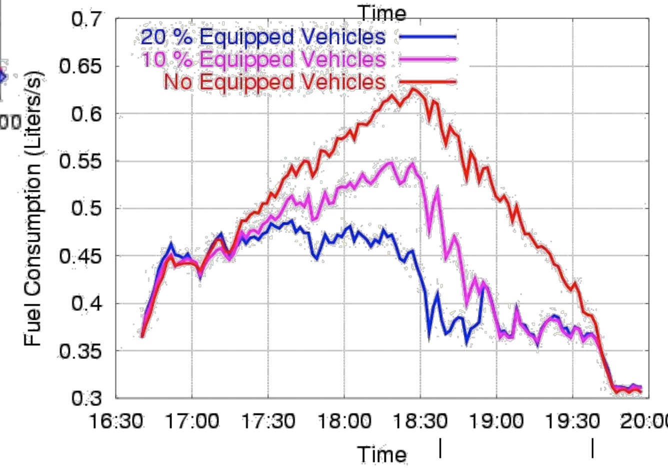
20% Equipped Vehicles



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

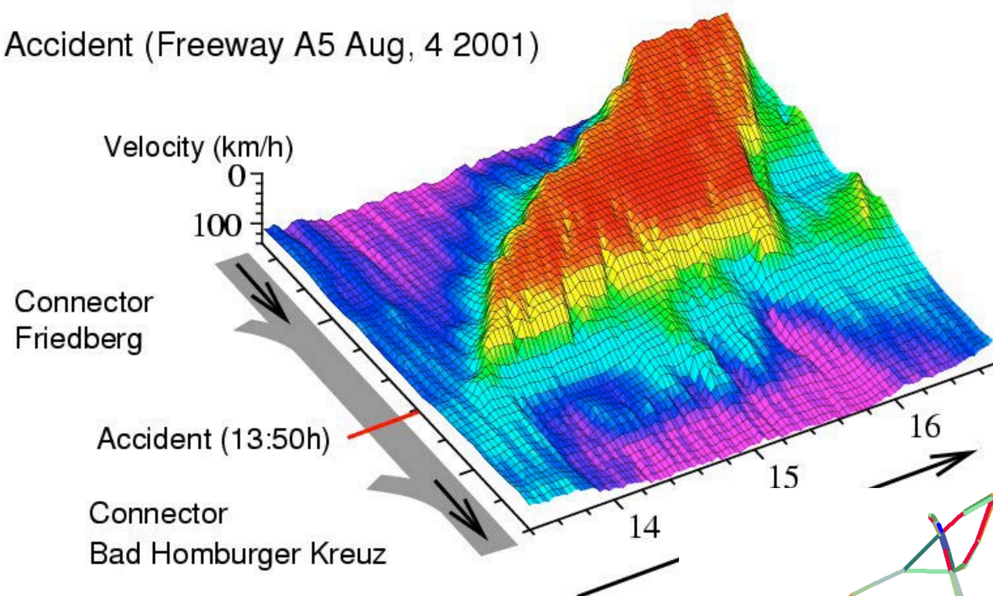


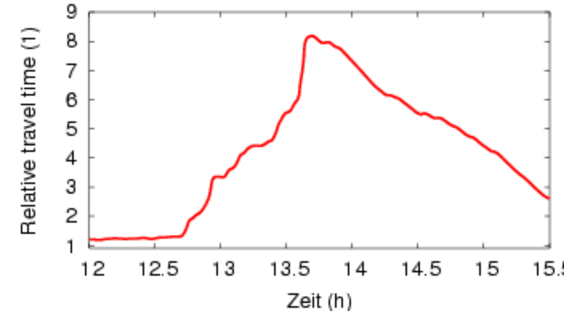


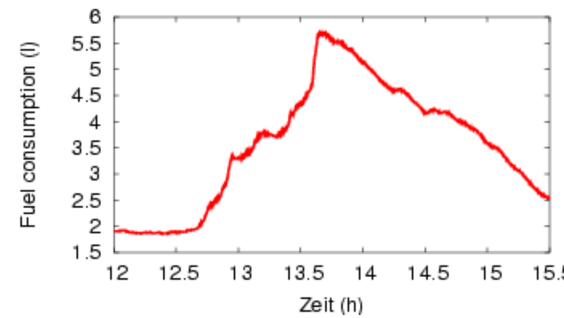


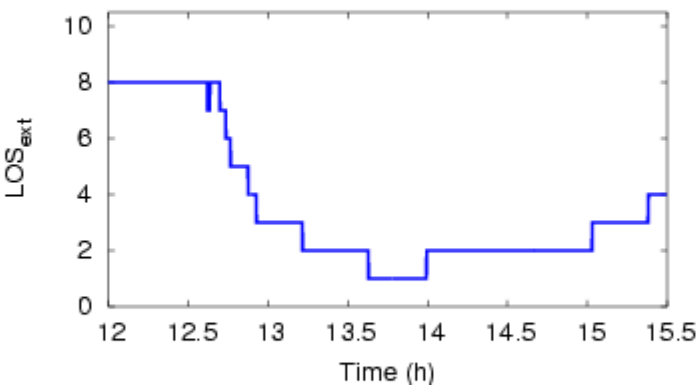
"Mechanism design", in cooperation with

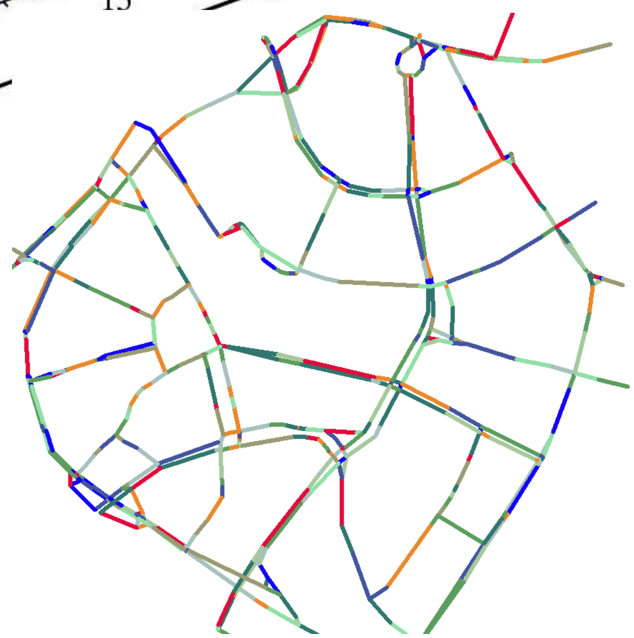
A Driver-Oriented Level of Service

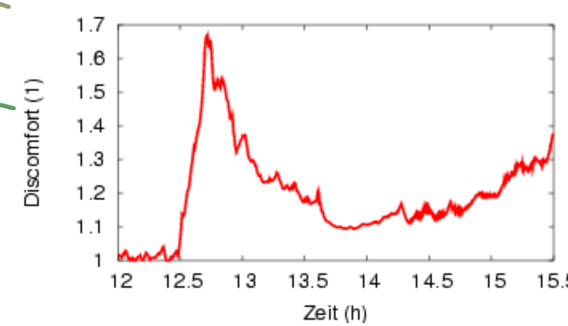








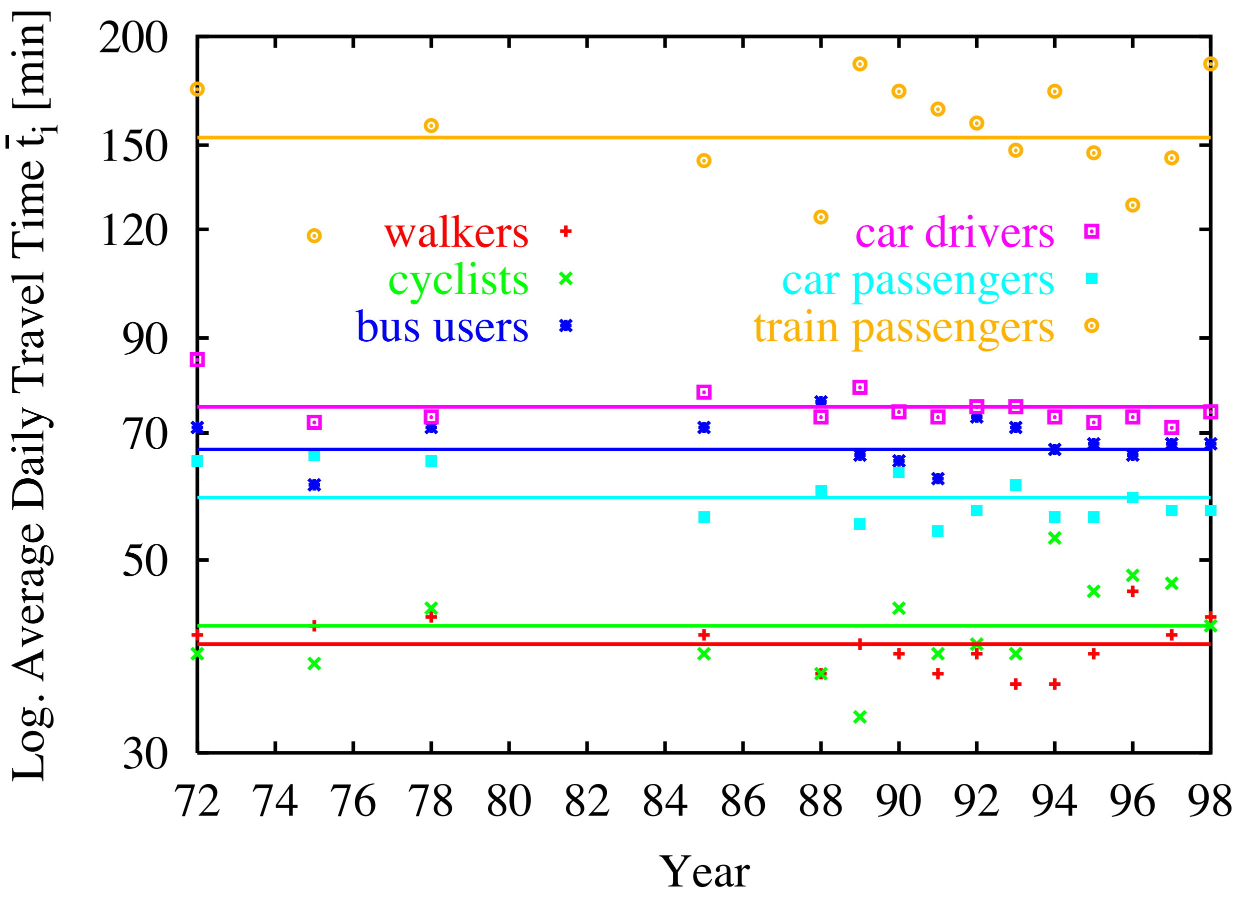




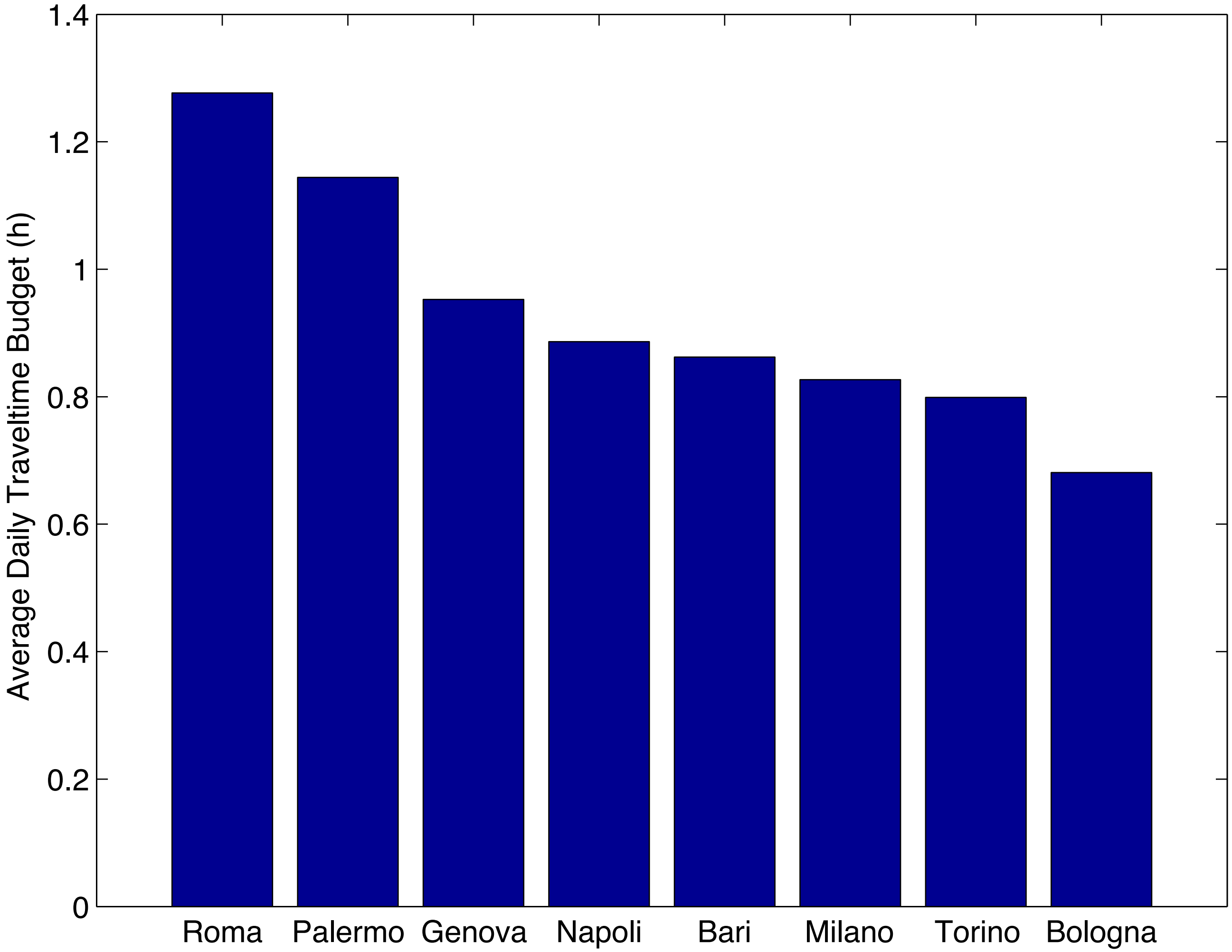
Travel Demand

Is Zahavi's Theory of a Constant Travel Time Budget Correct?

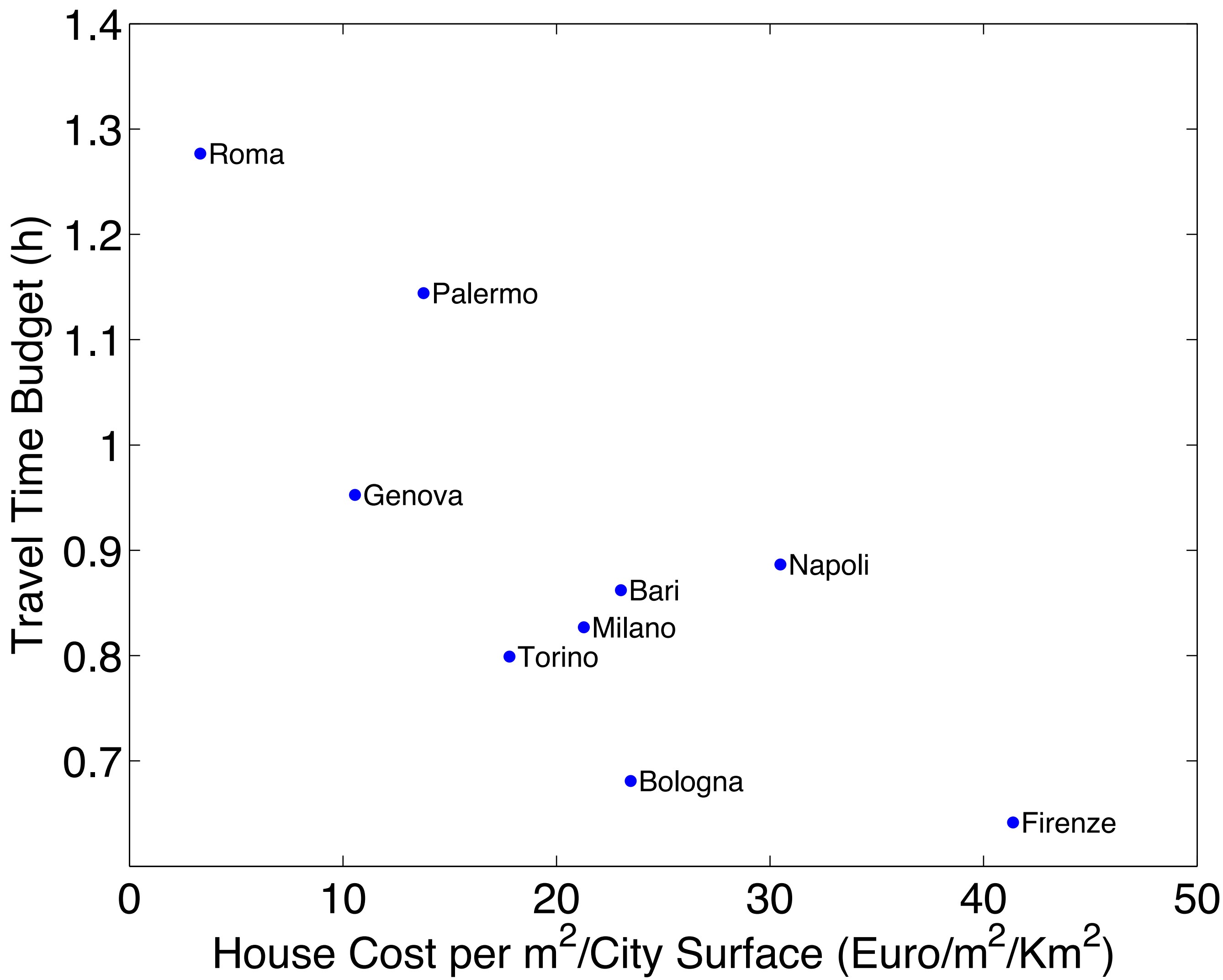
Zahavi and others: People spend about 1 hour traveling (on average), and they do it since ages. There is a fixed travel time budget.



The Travel Time Budget Is Not a Constant



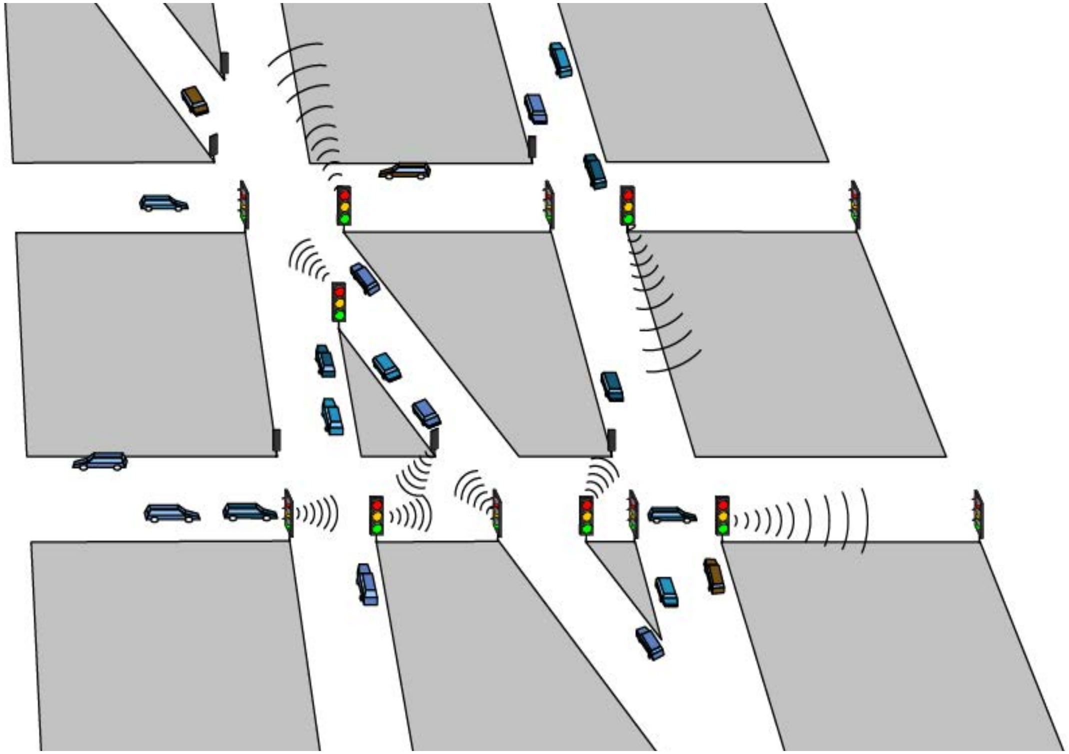
Travel Time Budget Depends on Housing Costs



Traffic Light Control

Adaptive Traffic Light Control

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



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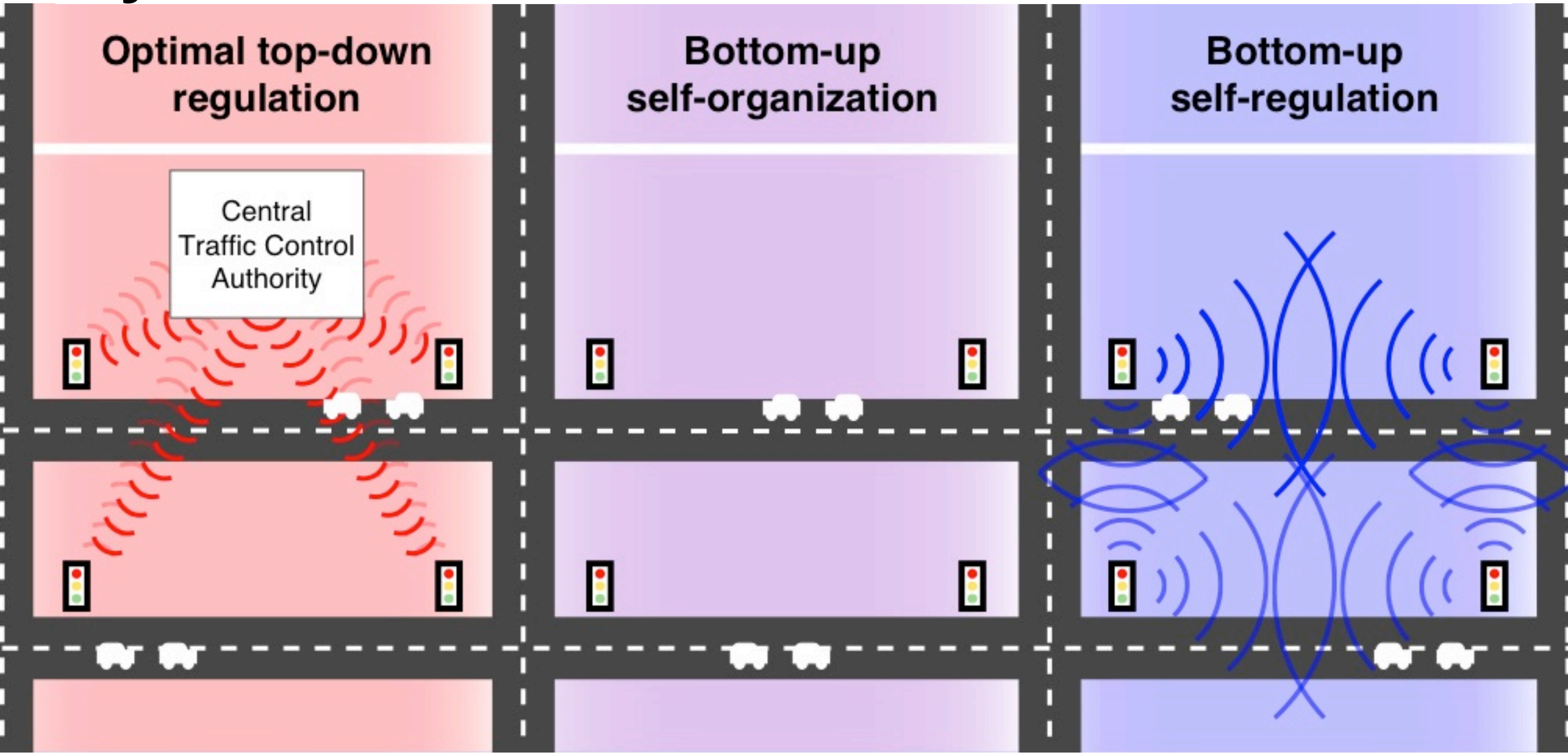
Comparing 3 Ways to Organize a Complex System

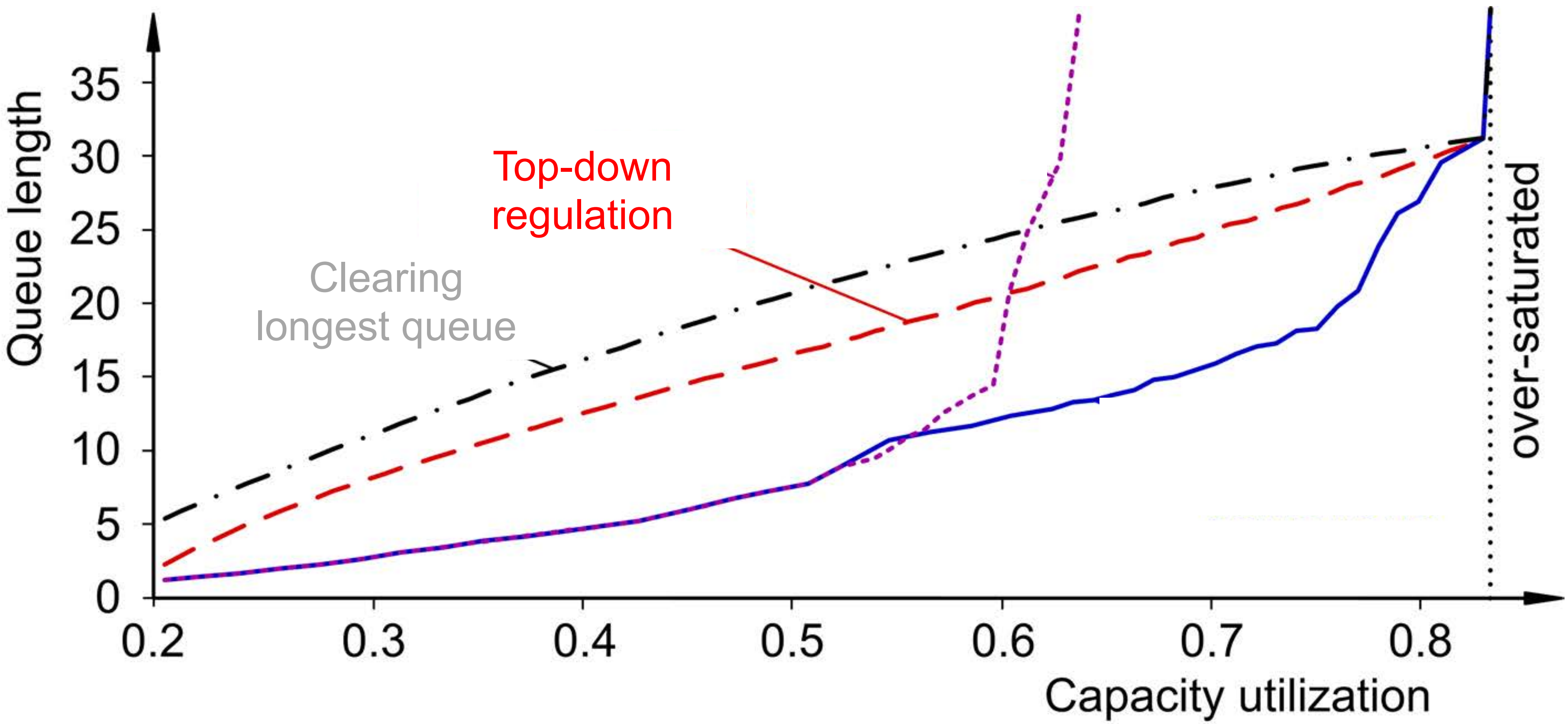


Central control, “benevolent dictator”

Travel time minimization, “homo economicus”

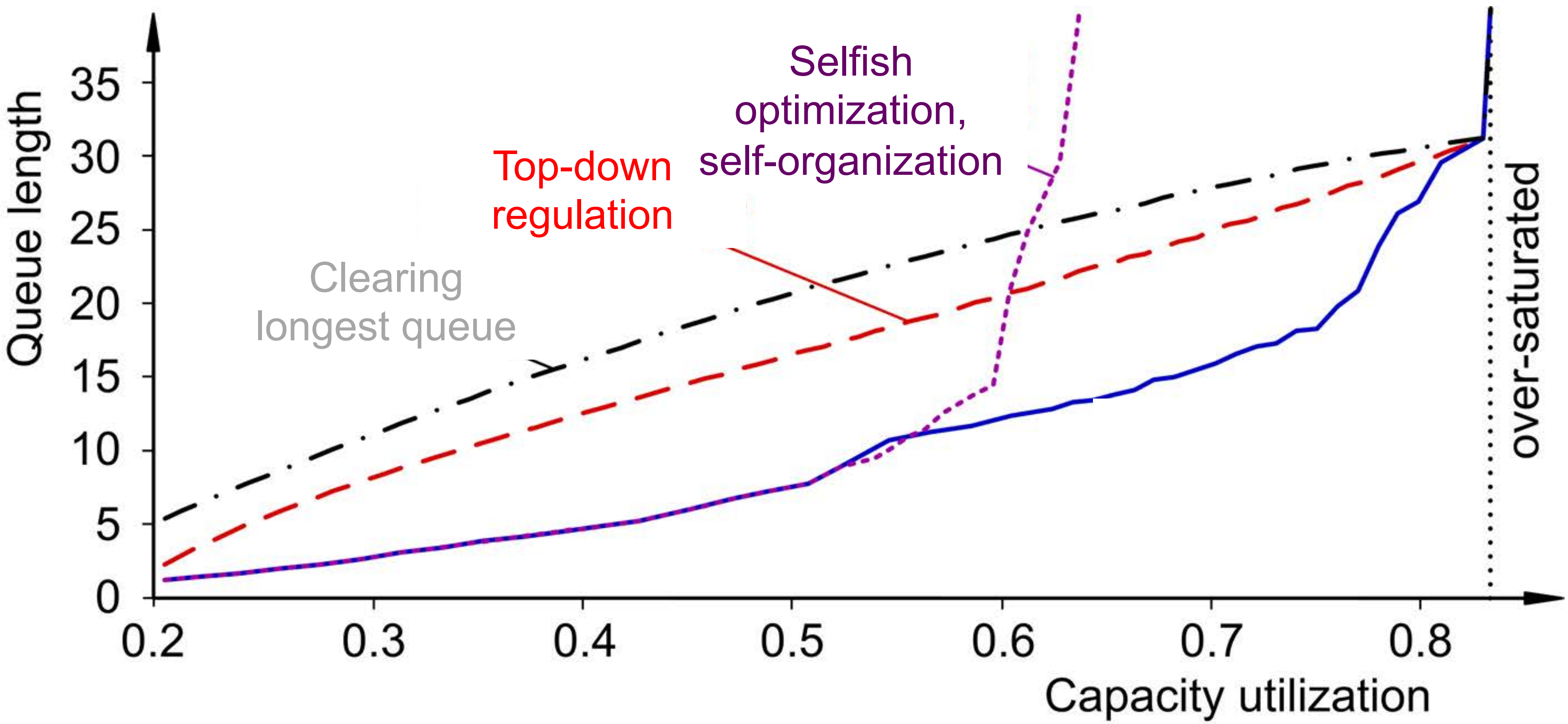
Same, but other-regarding coordination with neighbors

Bottom-Up Self-Regulation Can Outsmart Optimal Top-Down Control



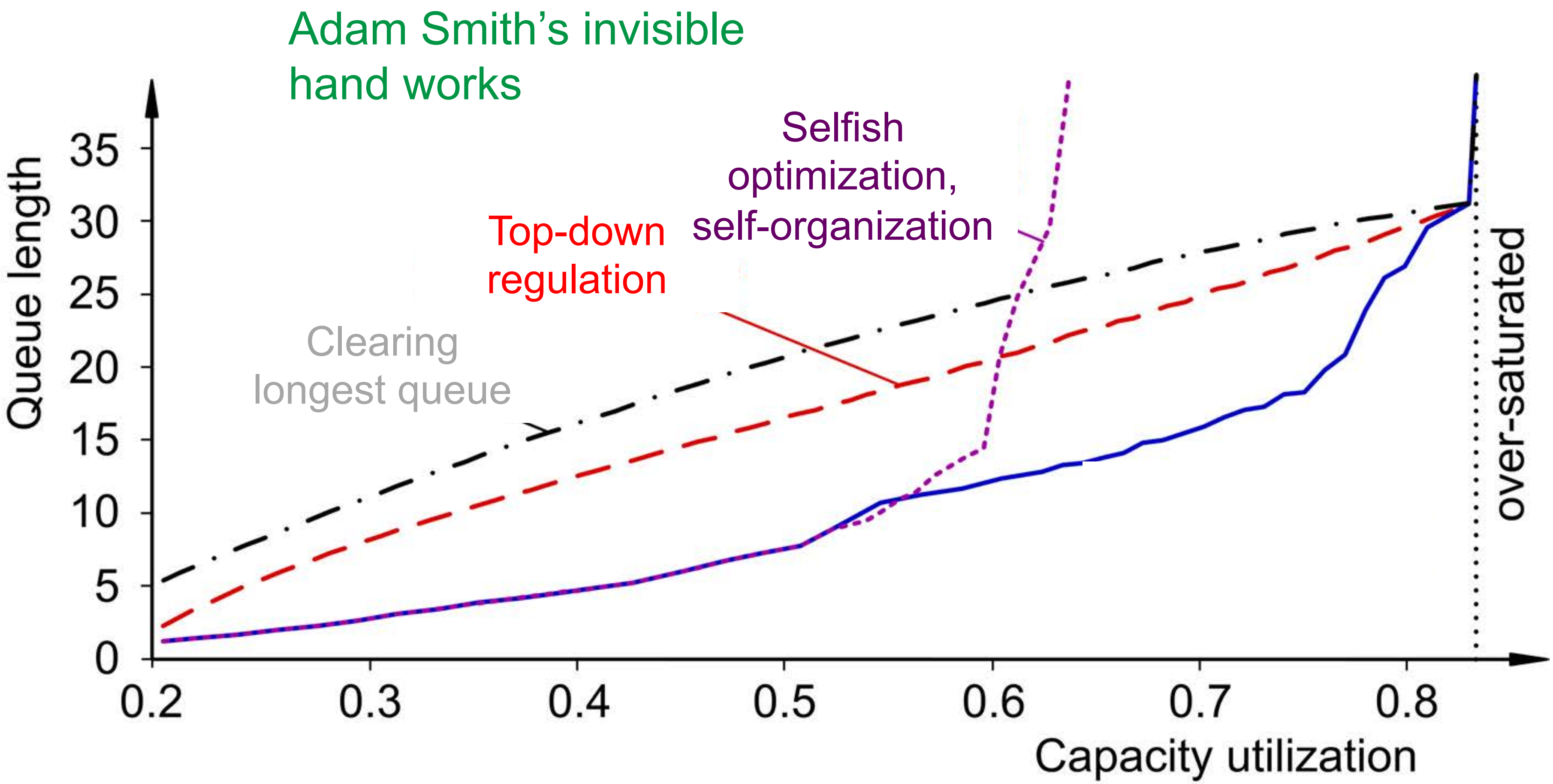
Stefan Lämmer and Dirk Helbing

Bottom-Up Self-Regulation Can Outsmart Optimal Top-Down Control

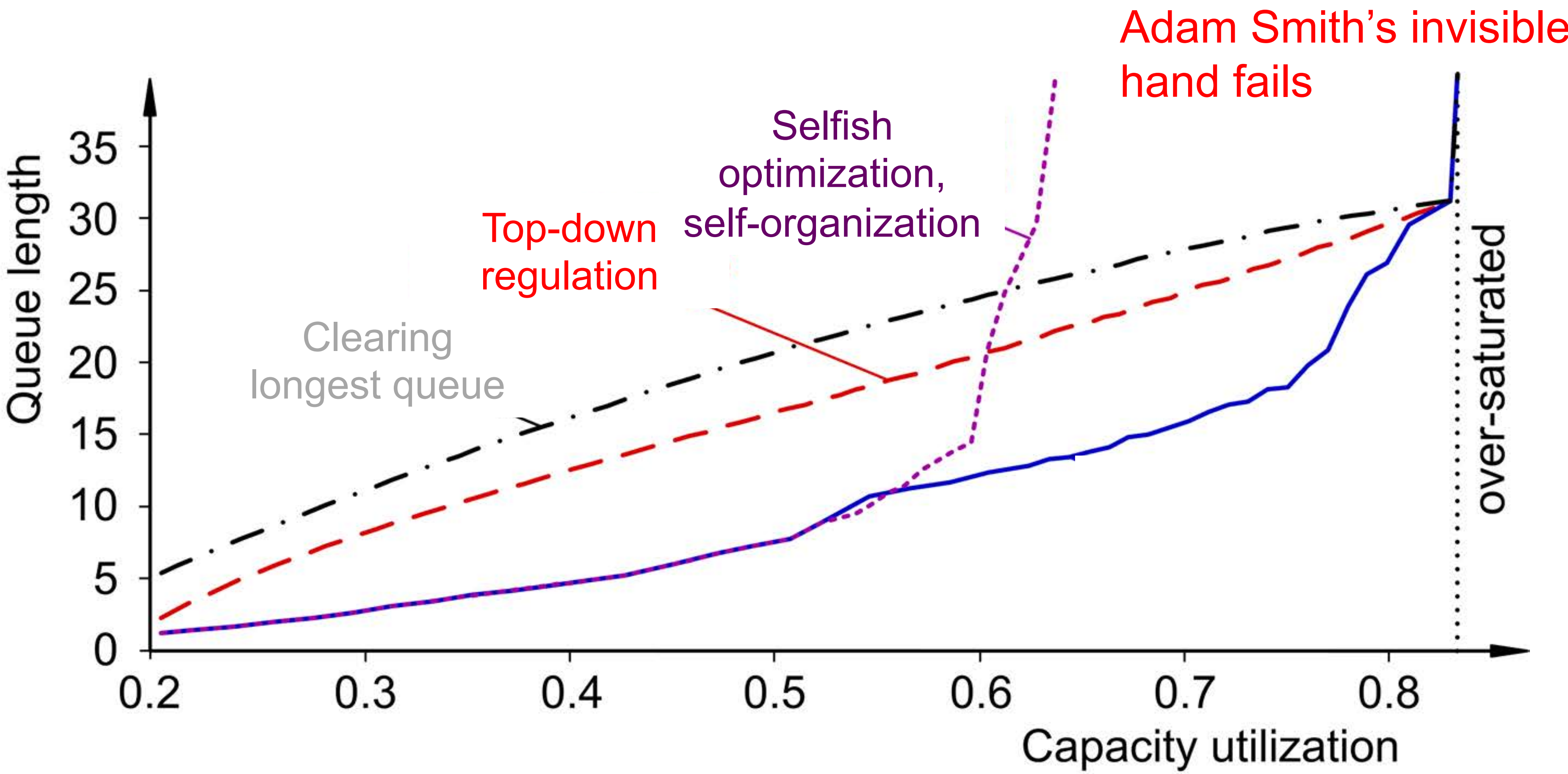


Stefan Lämmer and Dirk Helbing

Bottom-Up Self-Regulation Can Outsmart Optimal Top-Down Control

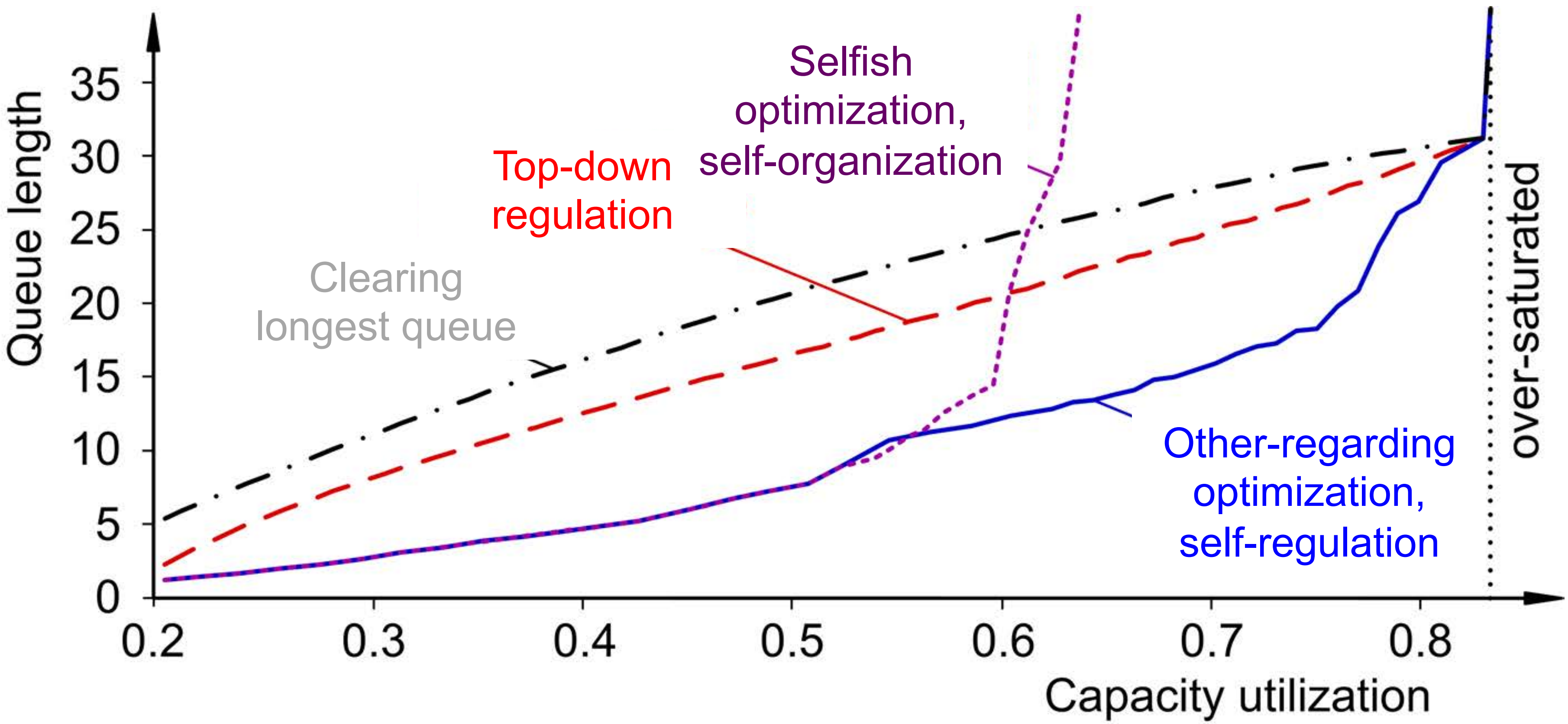


Bottom-Up Self-Regulation Can Outsmart Optimal Top-Down Control

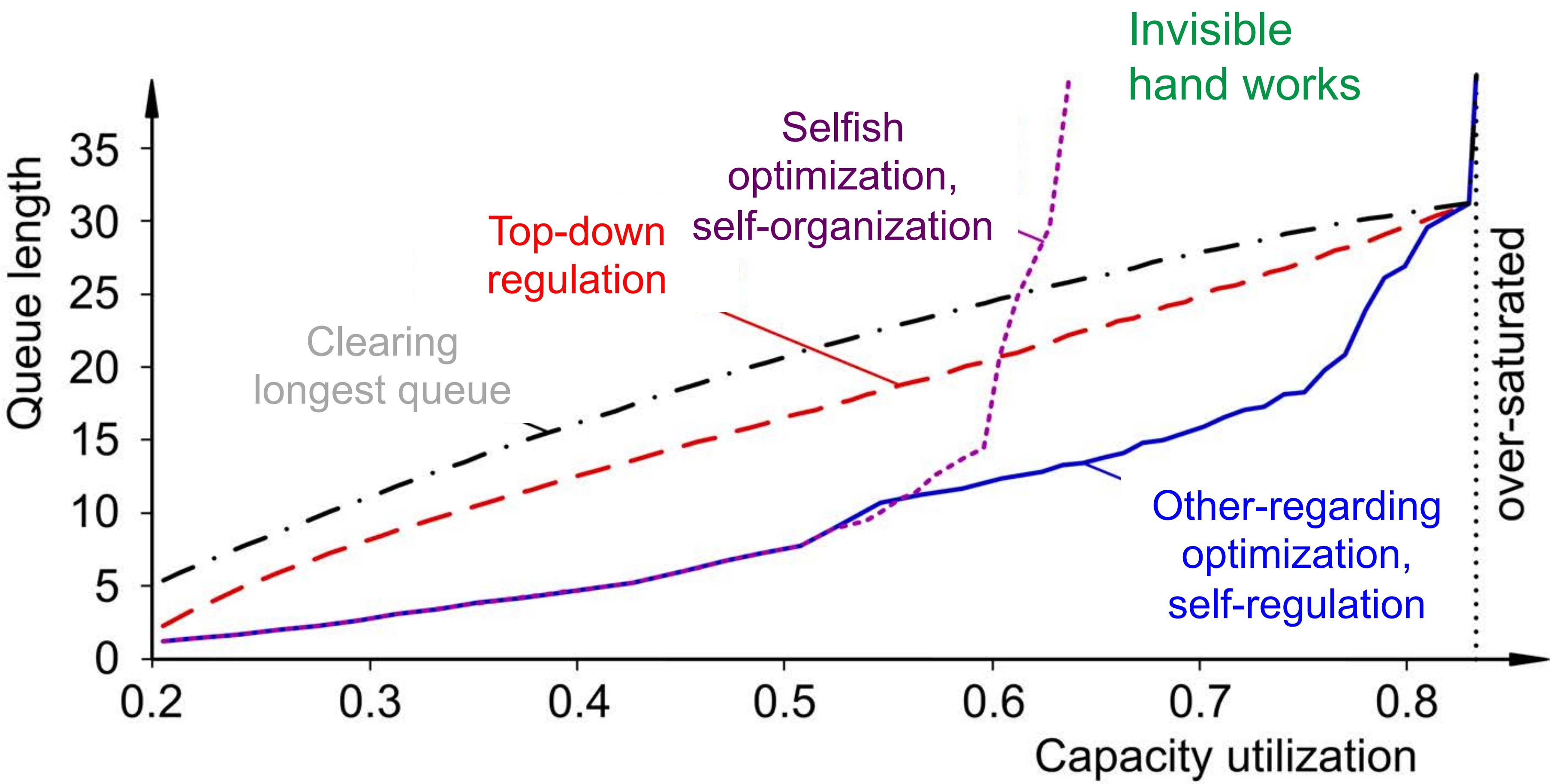


Stefan Lämmer and Dirk Helbing

Bottom-Up Self-Regulation Can Outsmart Optimal Top-Down Control



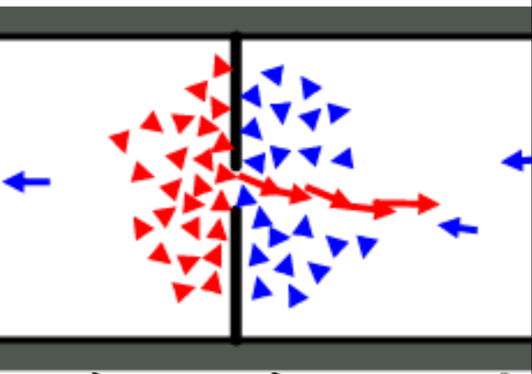
Bottom-Up Self-Regulation Can Outsmart Optimal Top-Down Control

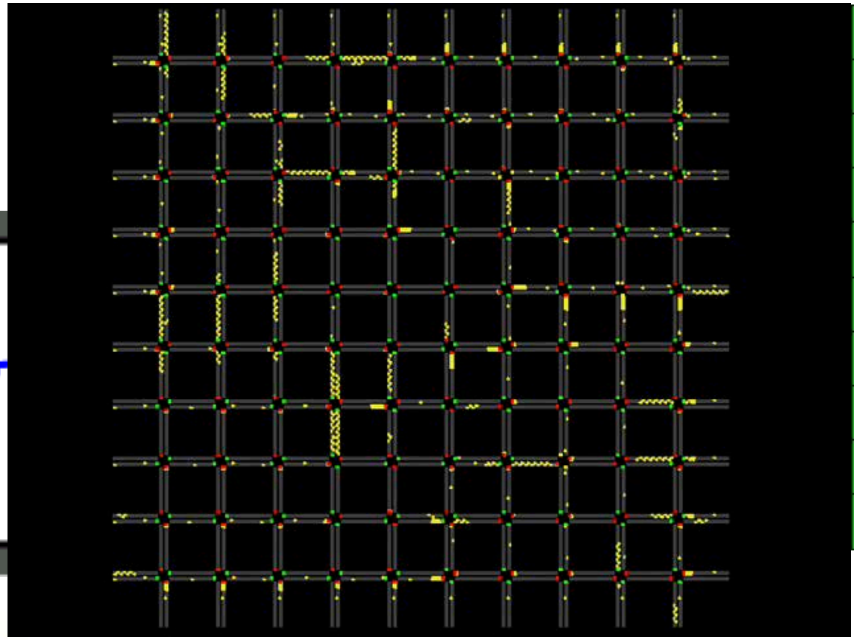


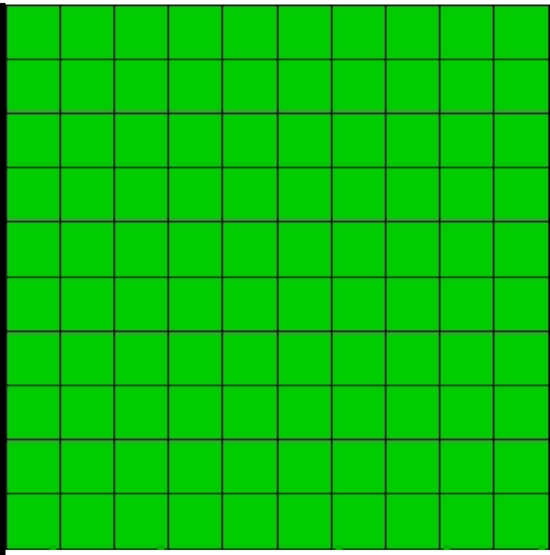
Stefan Lämmer and Dirk Helbing

Decentralized Concept of Self-Organized Traffic Light Control

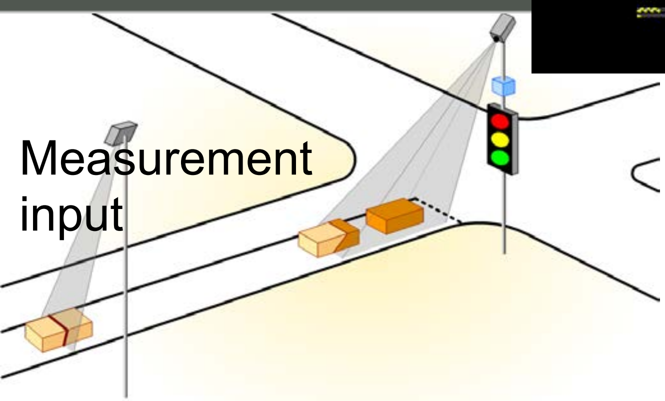
Inspiration: Self-organized oscillations at bottlenecks



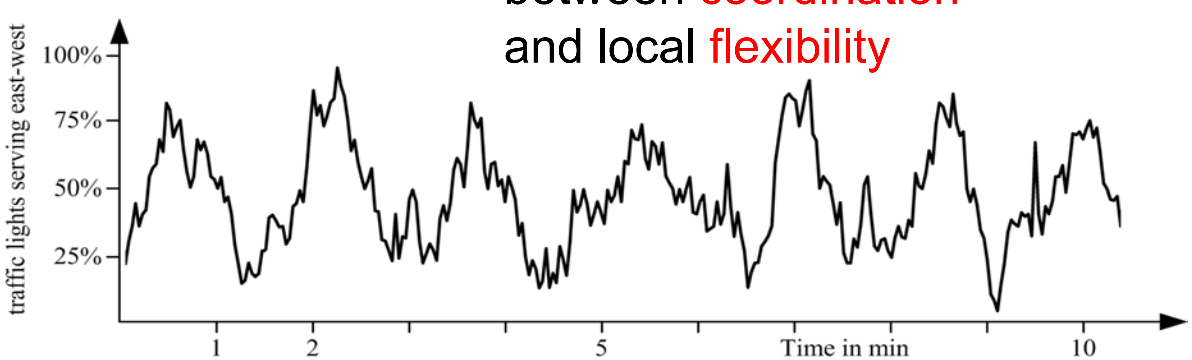




Measurement input

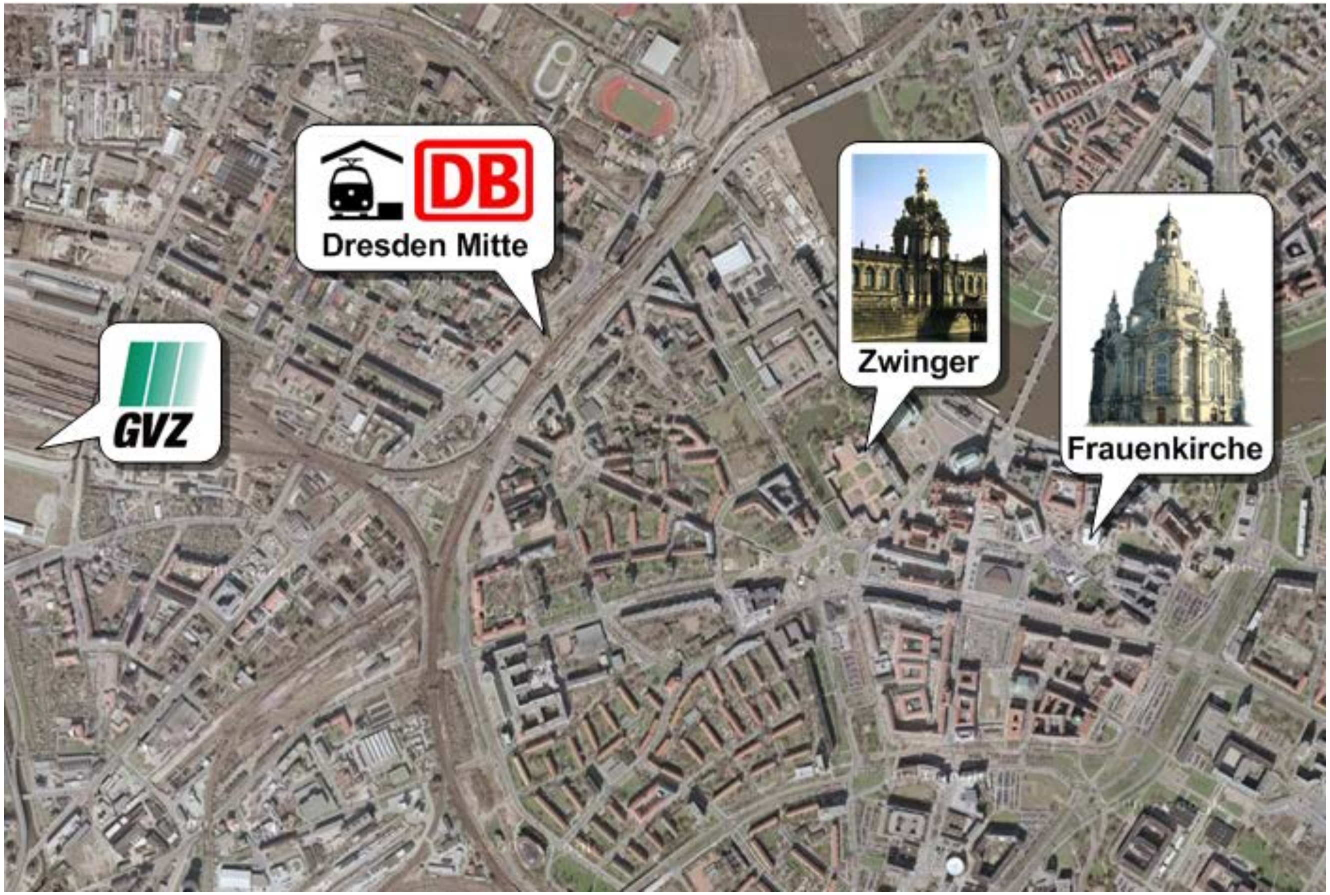


Optimal compromise between coordination and local flexibility

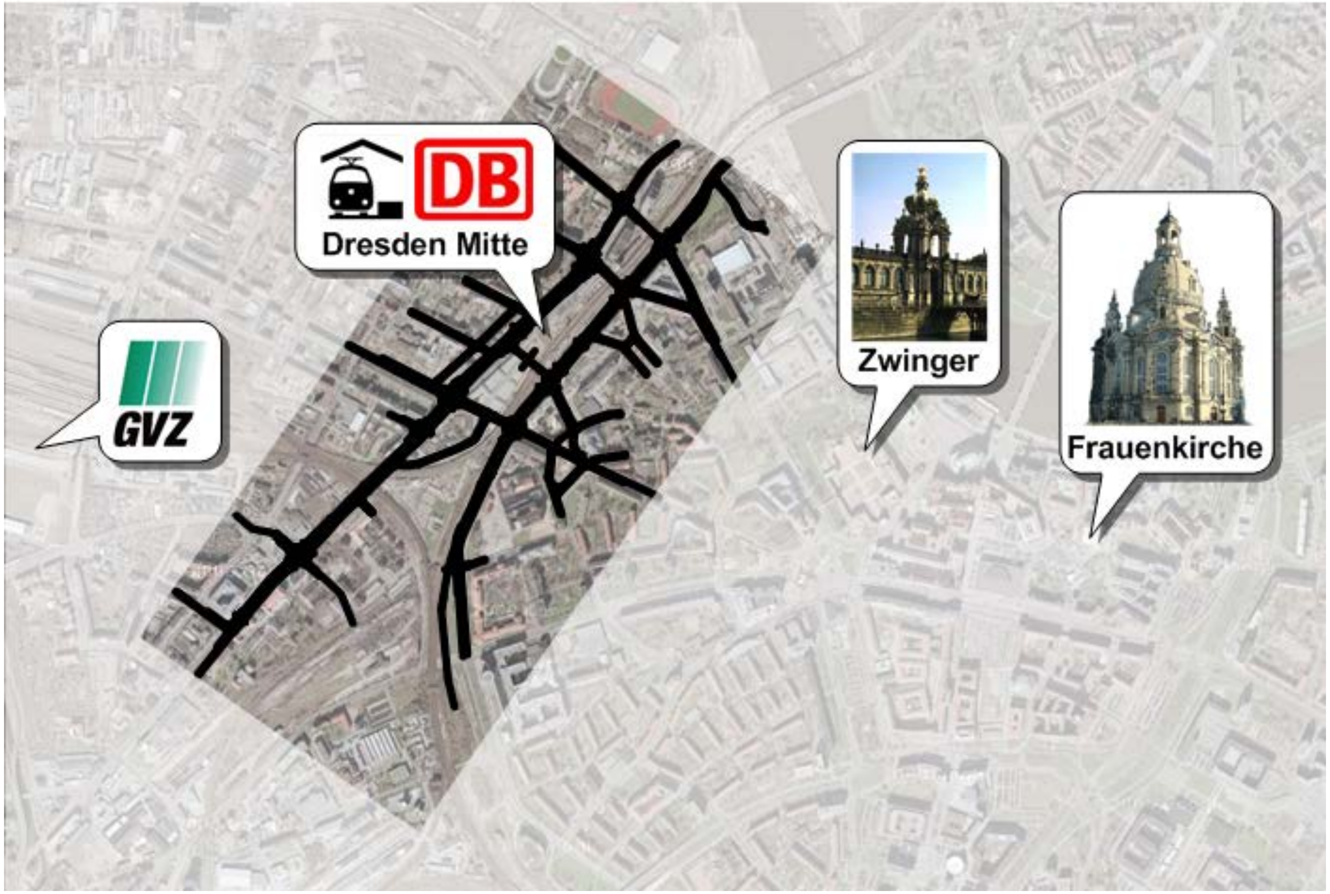


Published in *JSTAT* (2008)

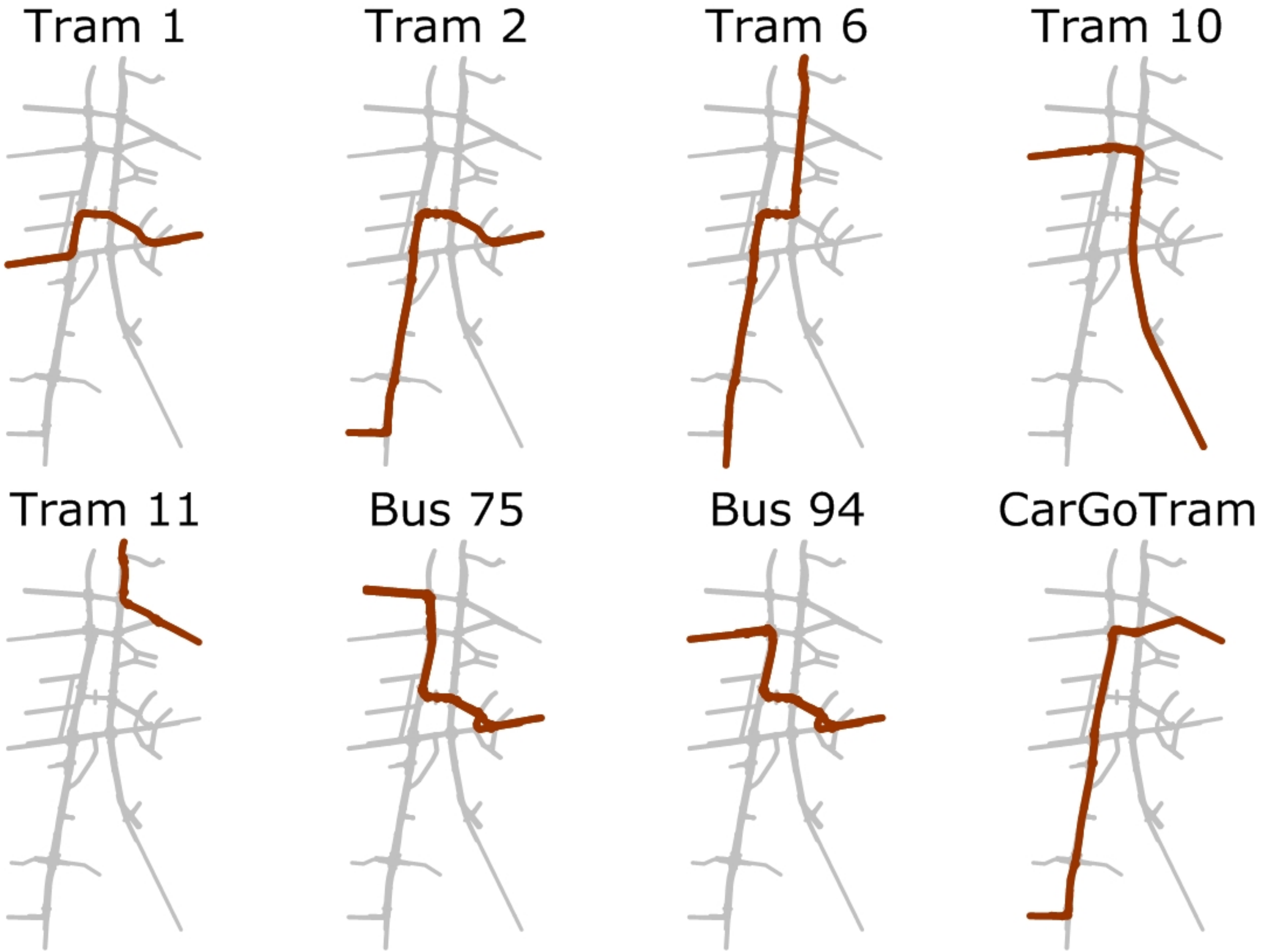
Towards Self-Organized Traffic Light Control in Dresden



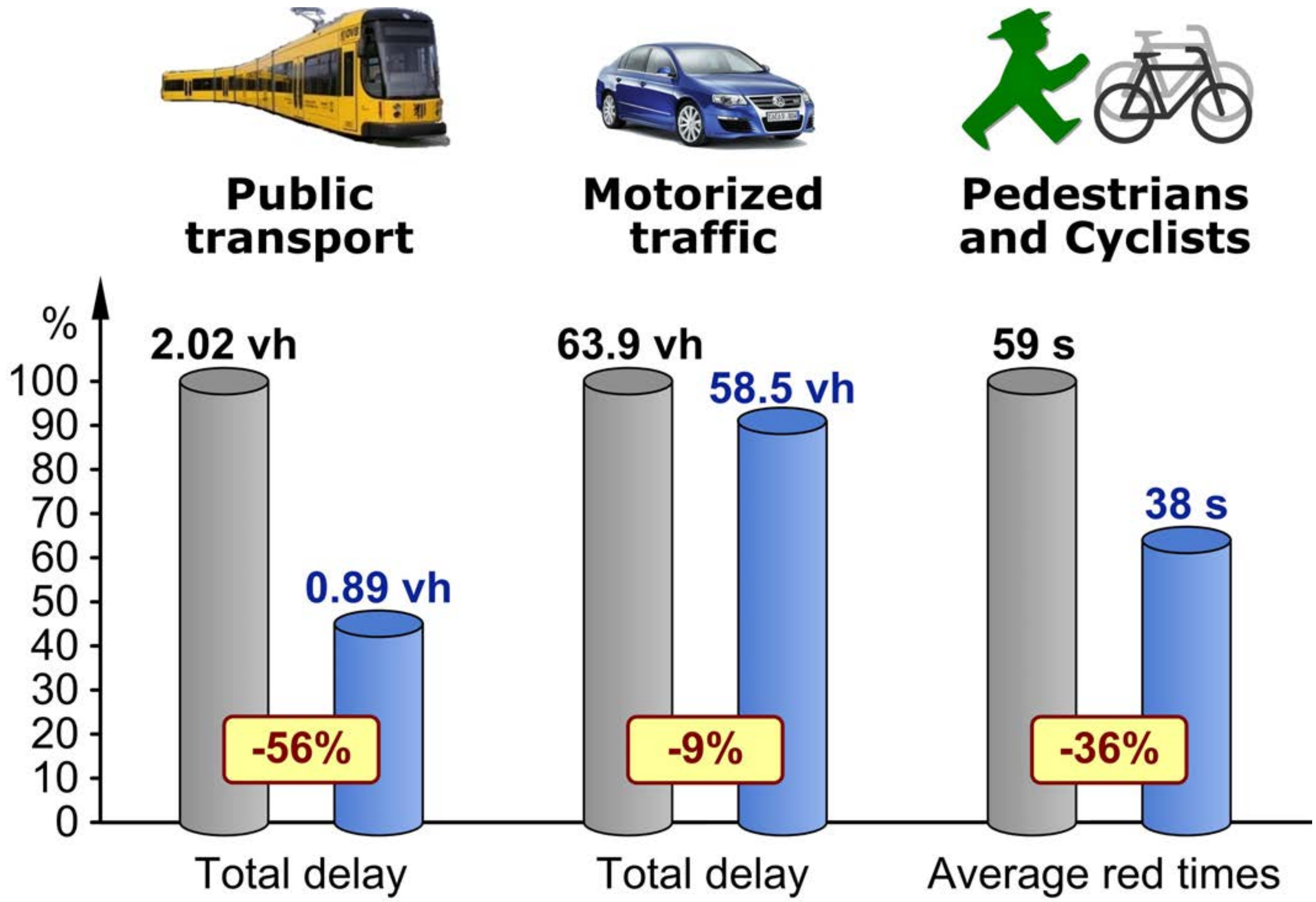
The Measurement and Control Area



Disturbance of Traffic Coordination by Bus and Tram Lines



Gain in Performance

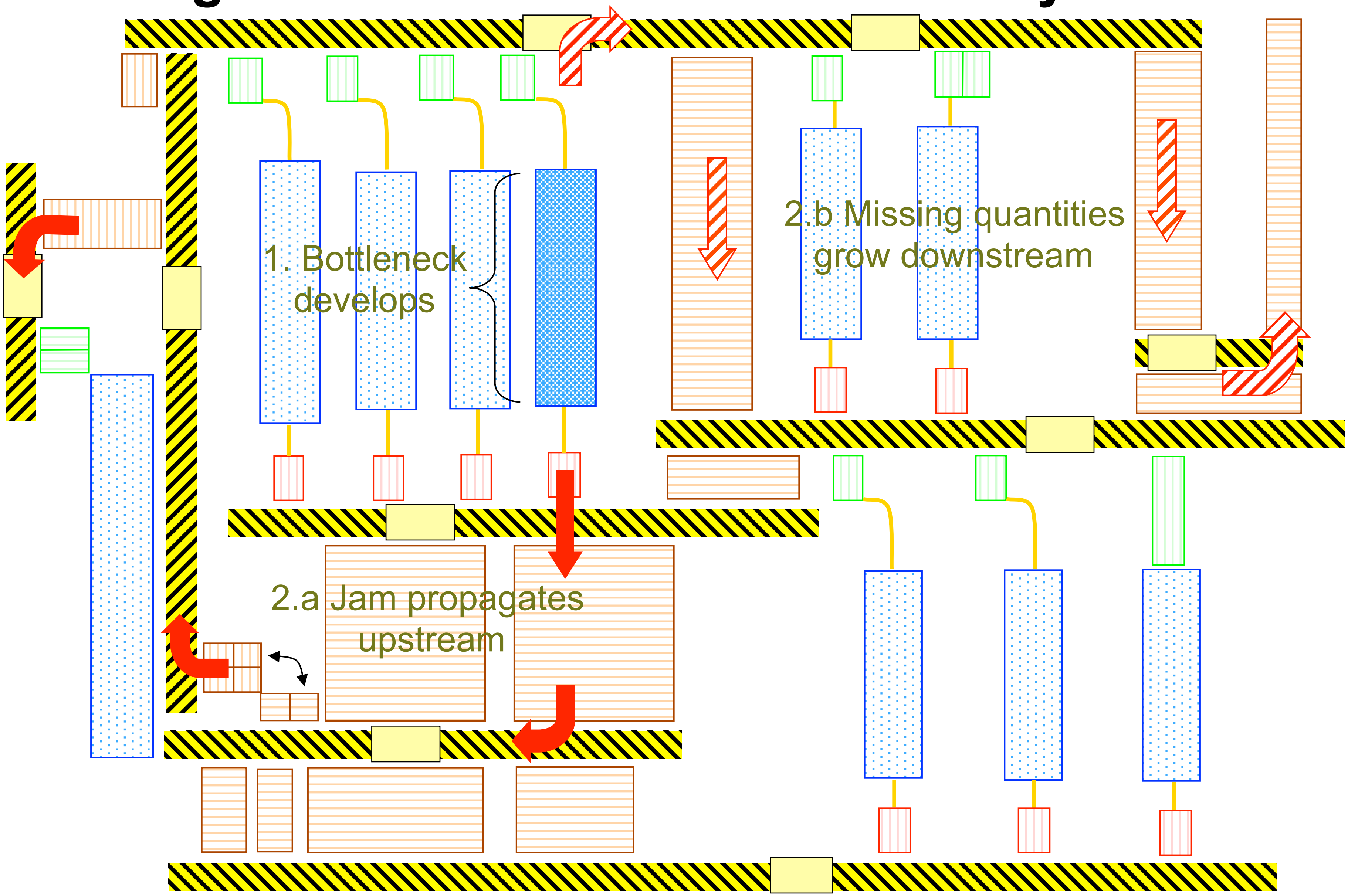


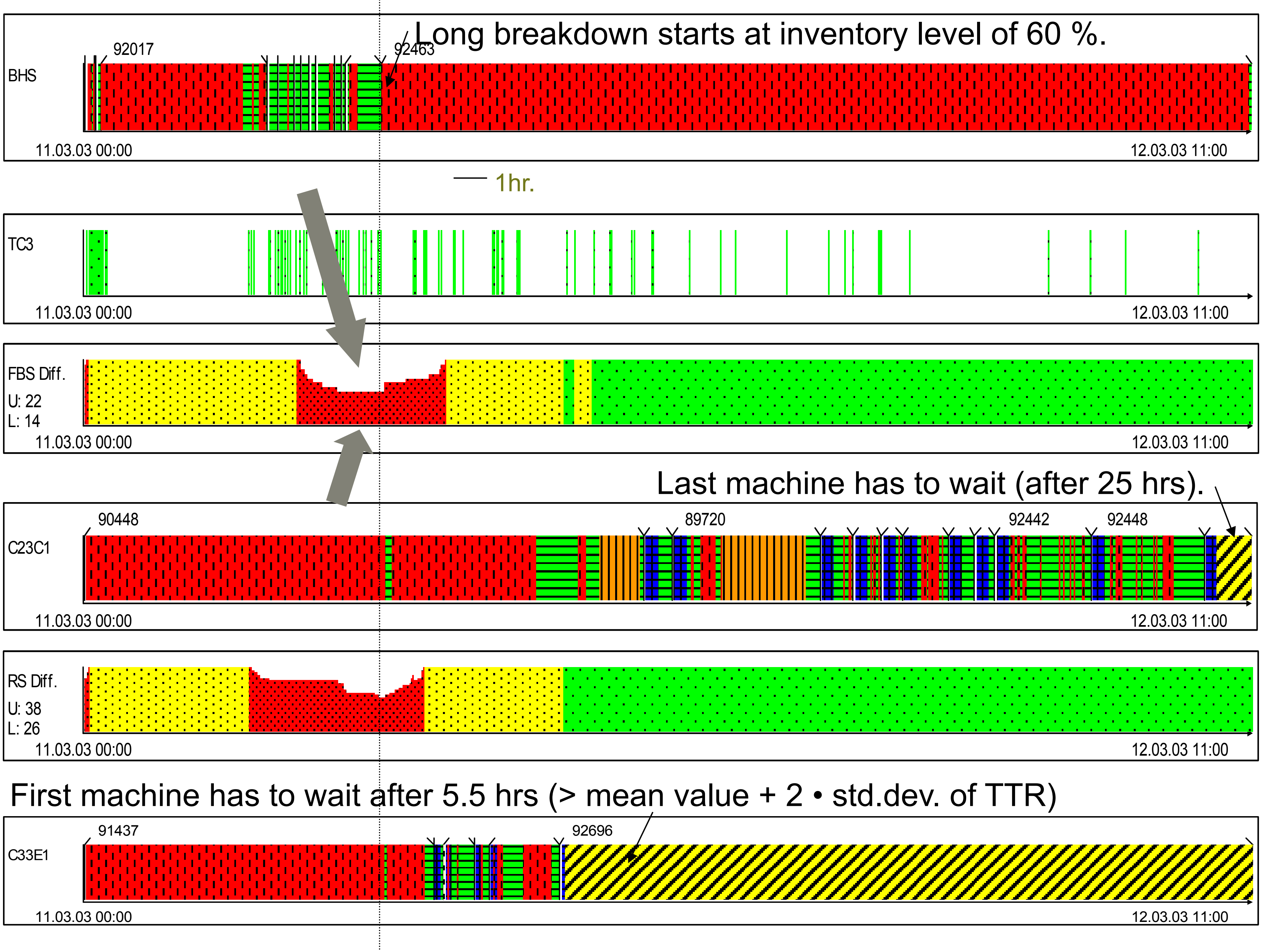
Production, Supply Chains, and Logistics as Traffic Problems

Analogies to Production Networks

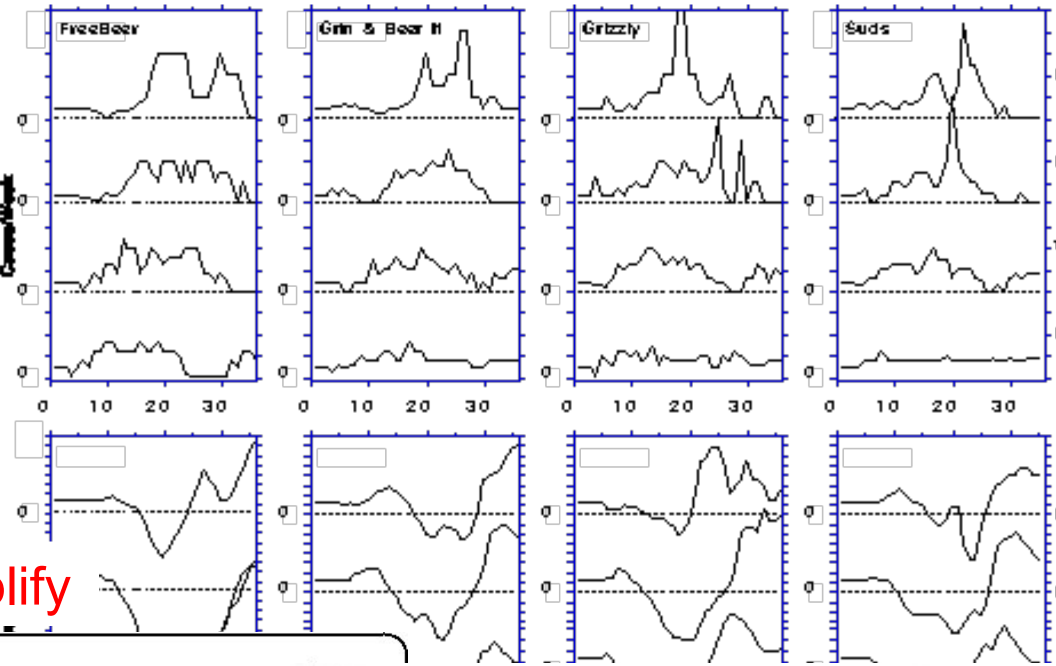
Road Networks		Production Networks
Directed Links:		
Road sections	⇔	Buffers
Travel- and delay time	⇔	Cycle time
Congestion, queues	⇔	Full buffers
Nodes:		
Junctions	⇔	Processing units
Different origin-destination	⇔	Different products flows
Conflicting flows	⇔	Conflicts in usage of gripper transfer cars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

Analogies of Production with Traffic Dynamics

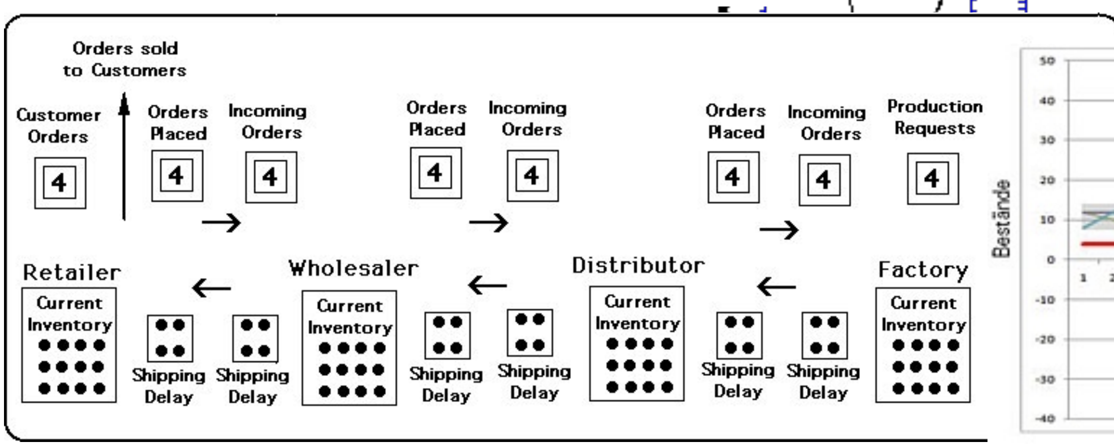


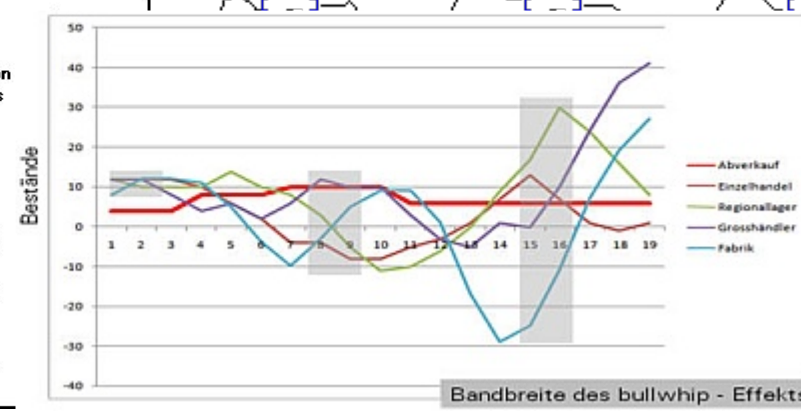

Long breakdown starts at inventory level of 60 %.
BHS
92017
92463
11.03.03 00:00
12.03.03 11:00
1hr.
TC3
11.03.03 00:00
12.03.03 11:00
FBS Diff.
U: 22
L: 14
11.03.03 00:00
12.03.03 11:00
Last machine has to wait (after 25 hrs).
C23C1
90448
89720
92442
92448
11.03.03 00:00
12.03.03 11:00
RS Diff.
U: 38
L: 26
11.03.03 00:00
12.03.03 11:00
First machine has to wait after 5.5 hrs (> mean value + 2 • std.dev. of TTR)
C33E1
91437
92696
11.03.03 00:00
12.03.03 11:00

John D. Sterman's Beer Game



Perturbations in demand amplify



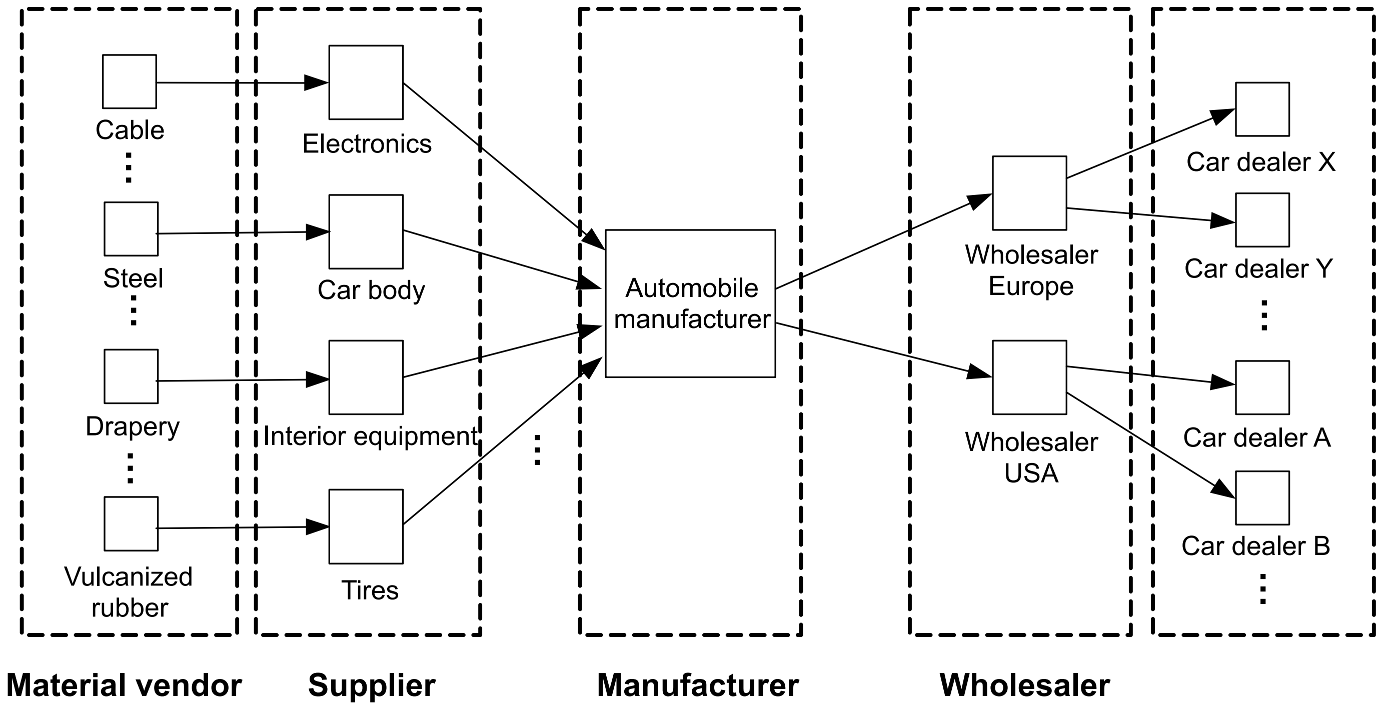


Material Flows in Supply Networks

Open questions:

- **Inventory** vs. **just in time** production?
- How important is the **network topology**?

Supply Chain as a network structure:



Modeling Supply Networks

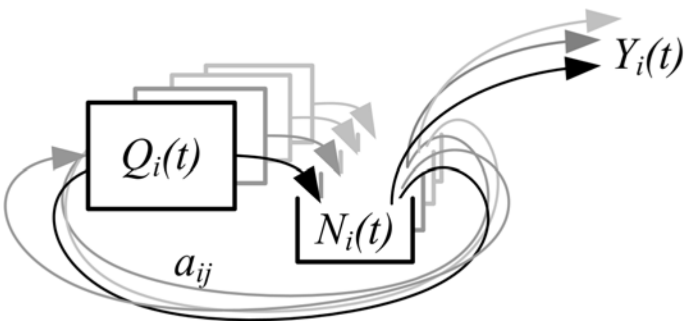
Conservation of resources

$$\dot{N}_i(t) = \underbrace{Q_i(t)}_{\text{supply}} - \underbrace{\sum_{j=1}^{m} a_{ij} Q_j(t)}_{\text{re-entrant}} - \underbrace{Y_i(t)}_{\text{outflow}}$$

(a_{ij})	input matrix $\mathbf{A}$
$N_i(t)$	inventory level
$Q_i(t)$	delivery rate
$Y_i(t)$	consumption rate
$P_i(t)$	price level

Adaptation of delivery rates

$$\frac{\dot{Q}_i(t)}{Q_i(t)} = \hat{\nu} \underbrace{\left(\frac{N_i^0}{N_i(t)} - 1 \right)}_{\text{deviations from desired level}} - \hat{\mu} \underbrace{\frac{\dot{N}_i(t)}{N_i(t)}}_{\text{temporal changes}}$$

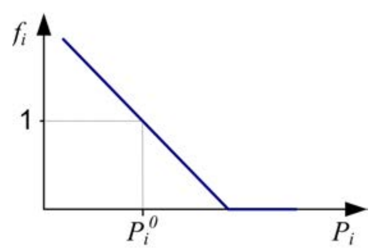


Adaptation of prices

$$\frac{\dot{P}_i(t)}{P_i(t)} = \nu \underbrace{\left(\frac{N_i^0}{N_i(t)} - 1 \right)}_{\text{deviations from desired level}} - \mu \underbrace{\frac{\dot{N}_i(t)}{N_i(t)}}_{\text{temporal changes}}$$

Consumption

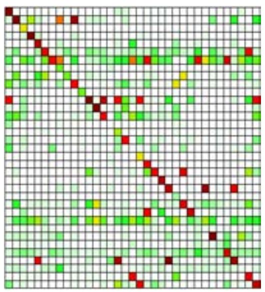
$$Y_i(t) = \left[Y_i^0 + \xi_i(t) \right] f_i\left(P_i(t)\right)$$

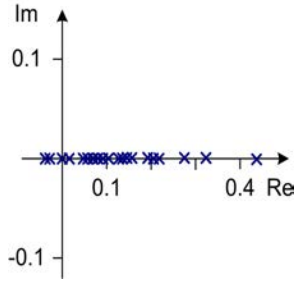


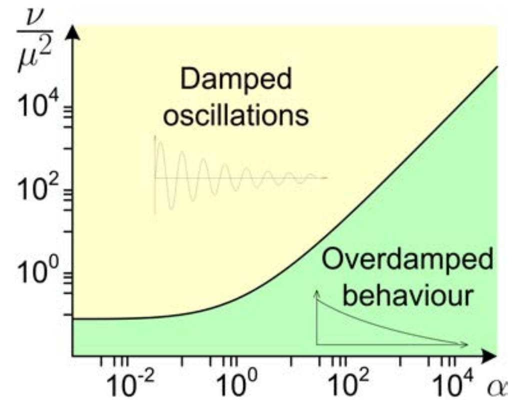
D. H., U. Witt, S. Lämmer, T. Brenner, *Physical Review E* **70**, 056118 (2004).

Network-Induced Oscillatory Behavior

Input matrices with **real** eigenvalues only

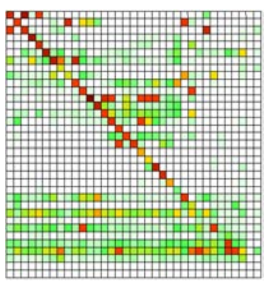


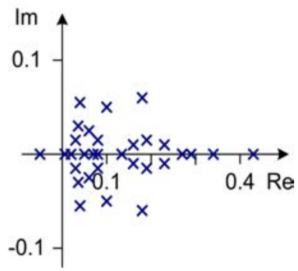


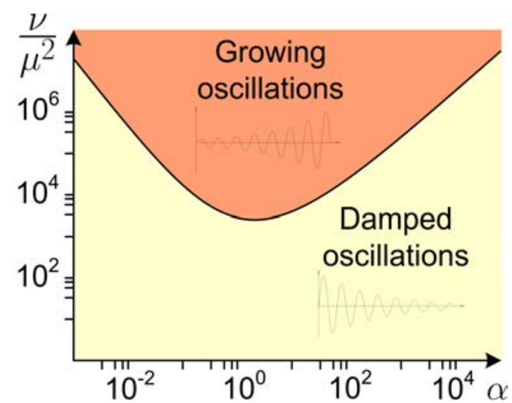


Overdamped behaviour possible.
Oscillations are **never growing**.

Input matrices with **complex** eigenvalues





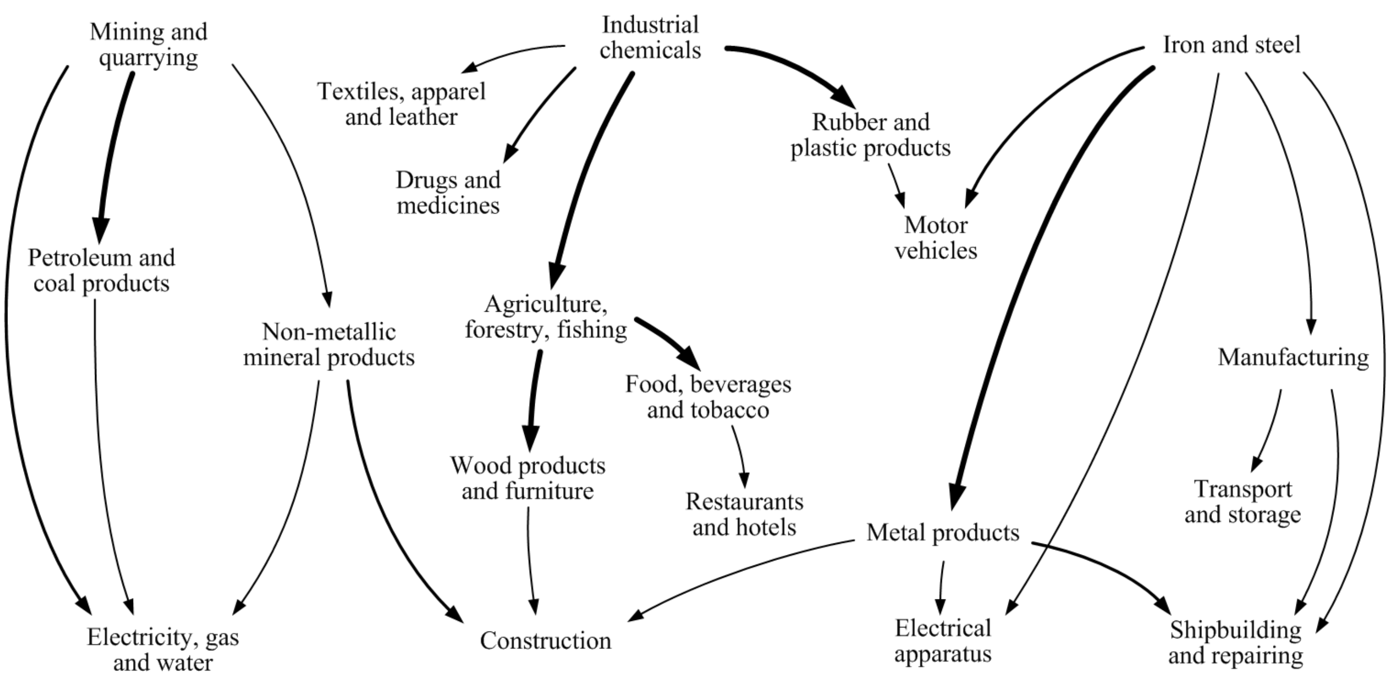


Always oscillating.
Growing oscillations are likely.

Global Logistic Networks: Recessions Are Like Traffic Jams of the Economy

Commodity flow (average of FRA, GER, JAP, UK, USA)

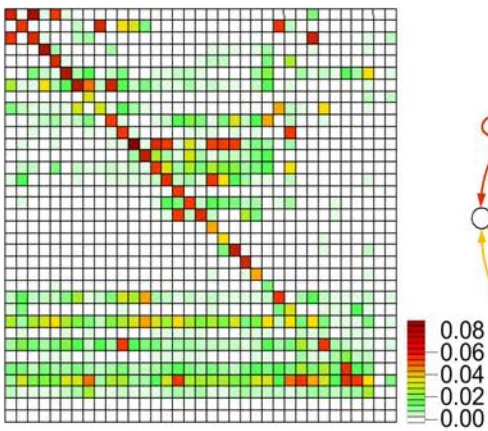
Network structure



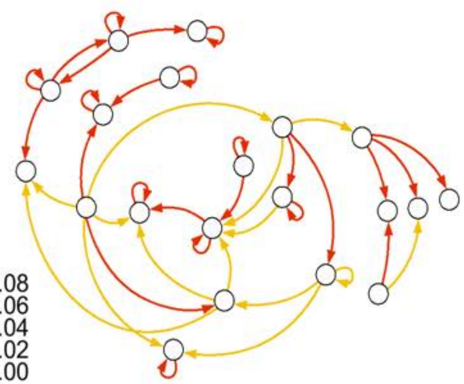
D. H., U. Witt, S. Lämmer, T. Brenner, *Physical Review E* **70**, 056118 (2004).

Business Cycles as Result of Network Flows

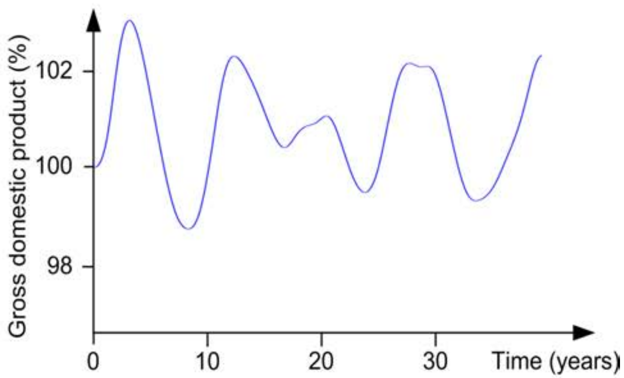
Business cycles because of the structure of production networks?



Input output matrix

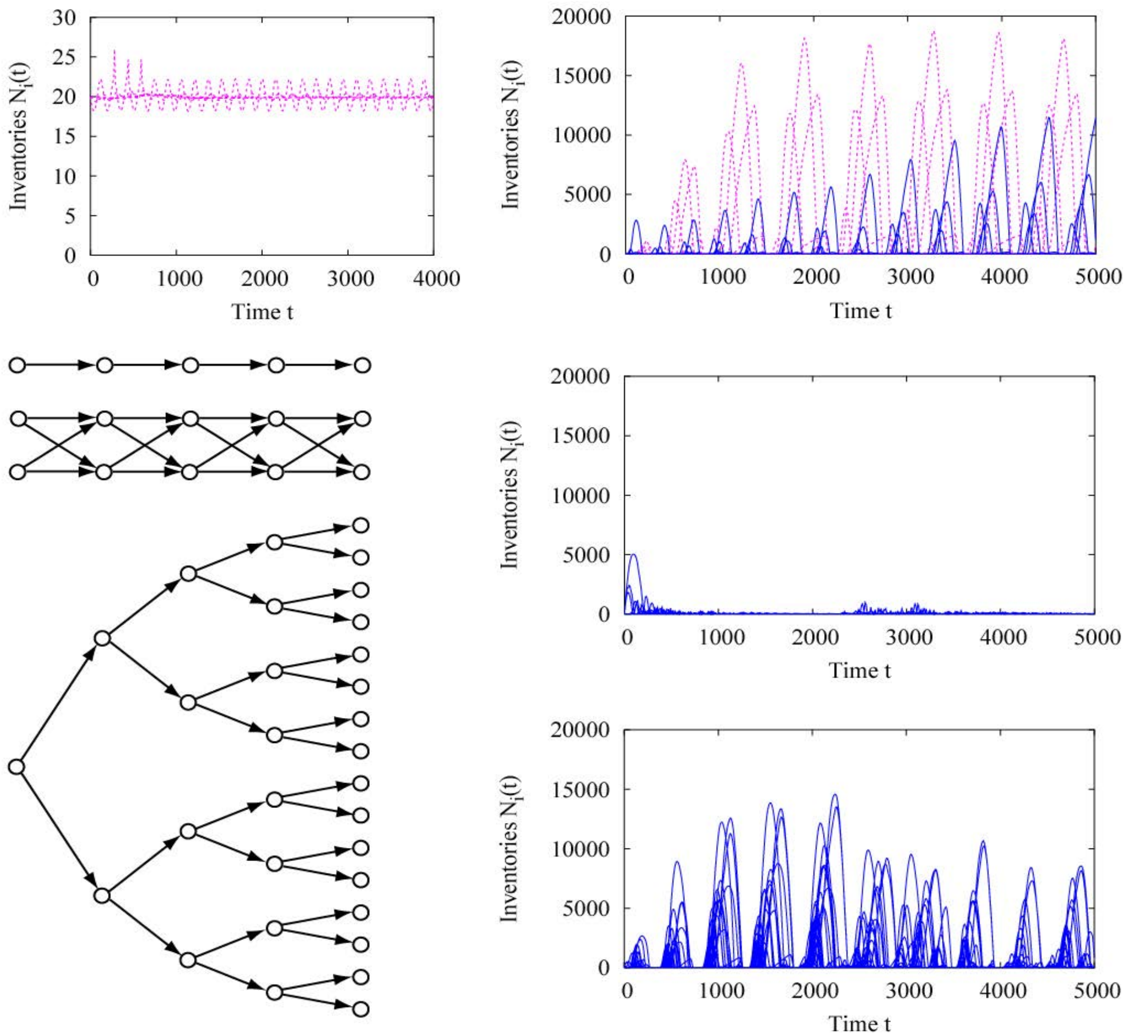


Related delivery network



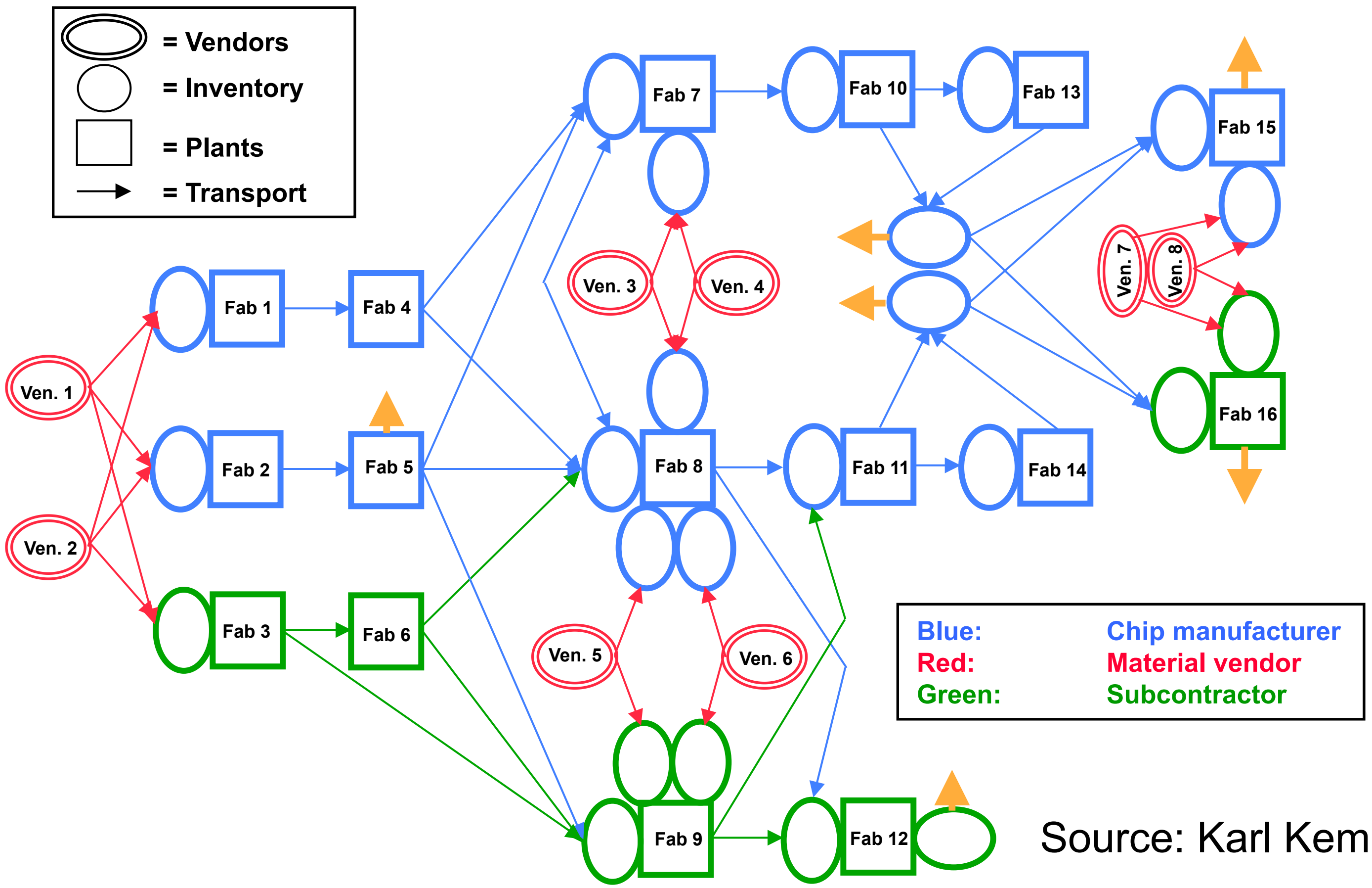
Resulting oscillations in the gross domestic product

Structure of Supply Network Can Stabilize



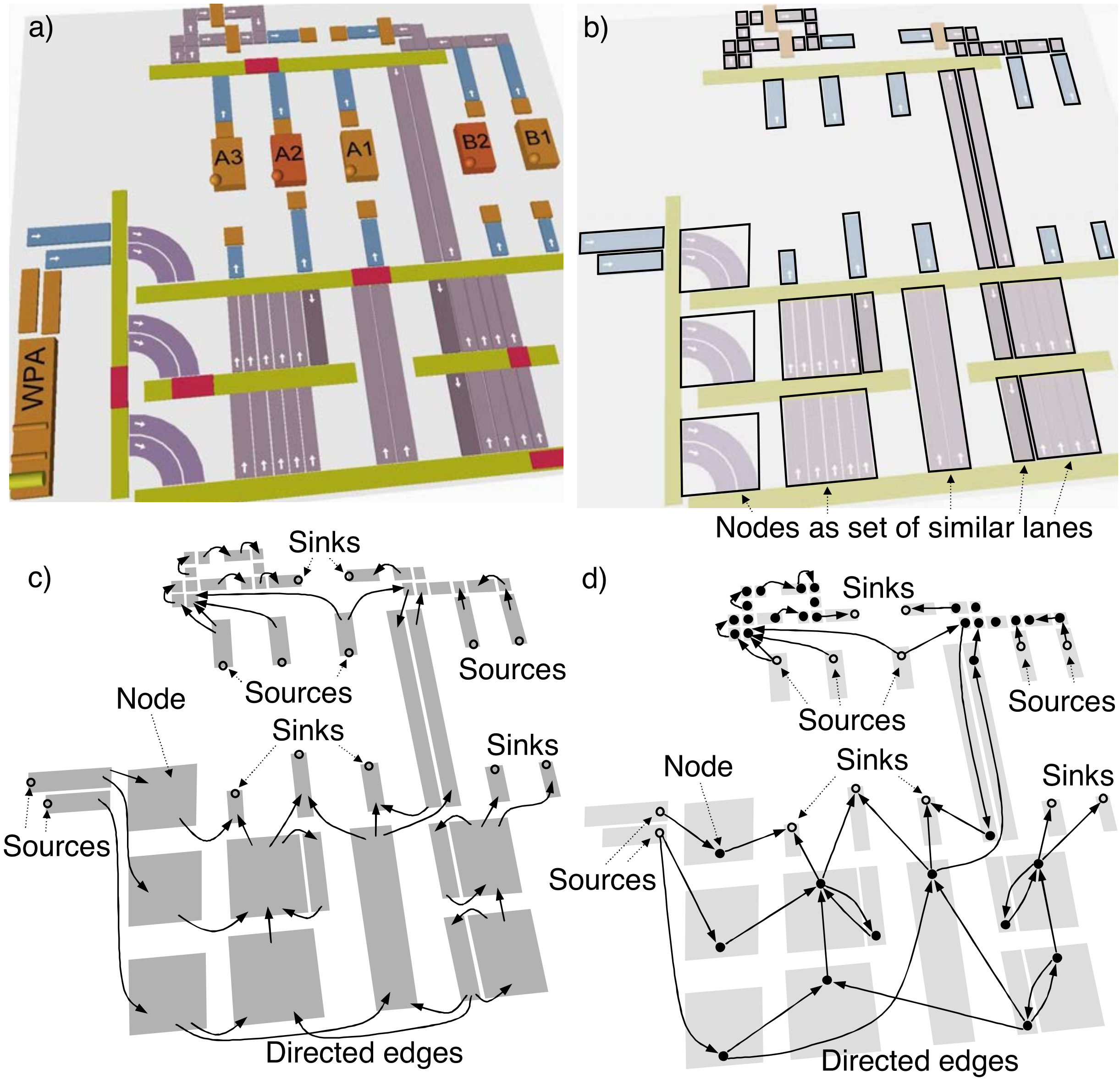
D. H., *New Journal of Physics* **5.90**, 1-28 (2003).

Redundancy Matters: Distribution Network of Intel Technologies



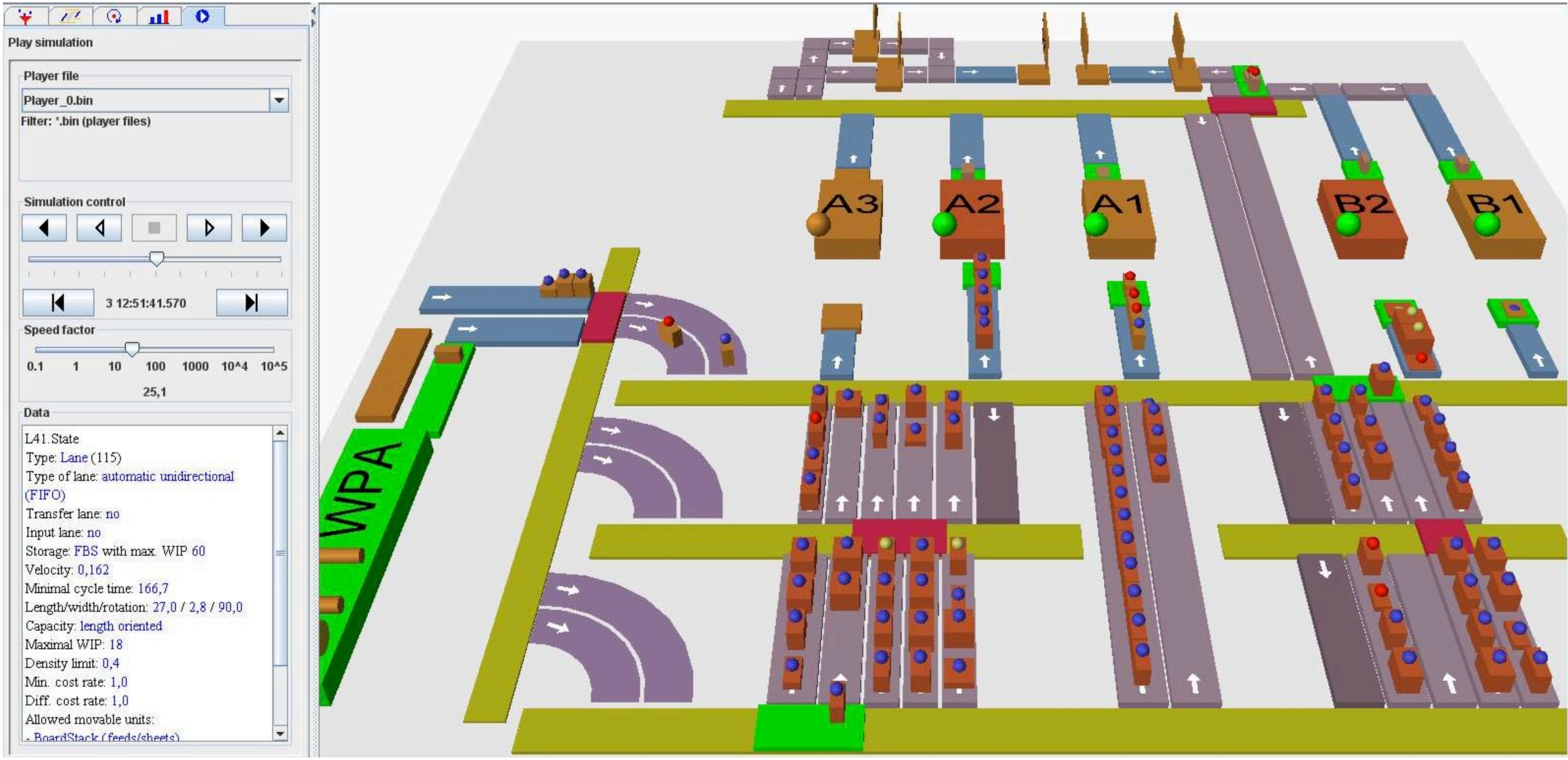
Source: Karl Kempf

Network Representation of A Production Plant



T. Seidel,
J. Hartwig,
R.L. Sanders,
DH

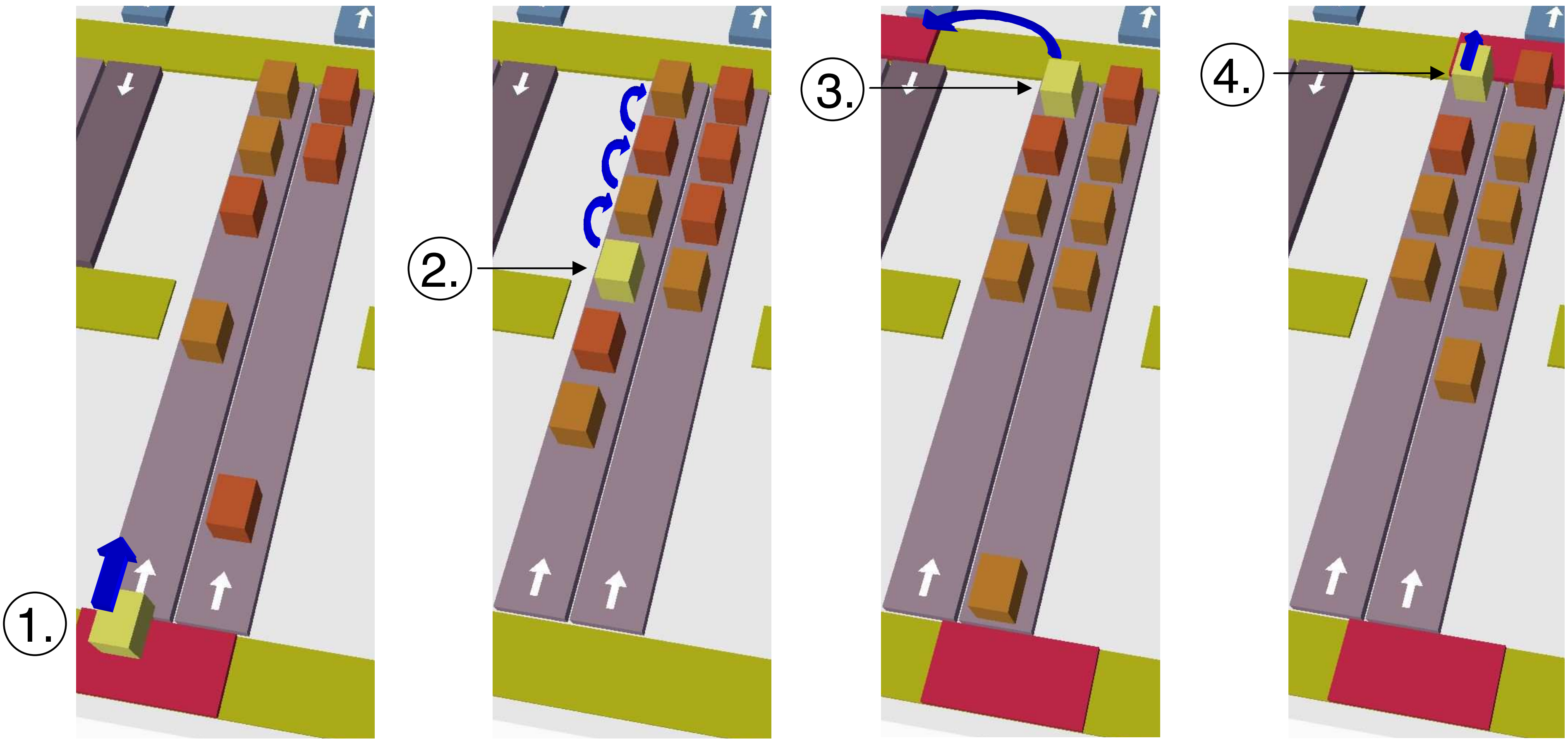
Agent-Based Factory Simulation of Self-Organized Production



T. Seidel, J. Hartwig, R.L. Sanders, DH

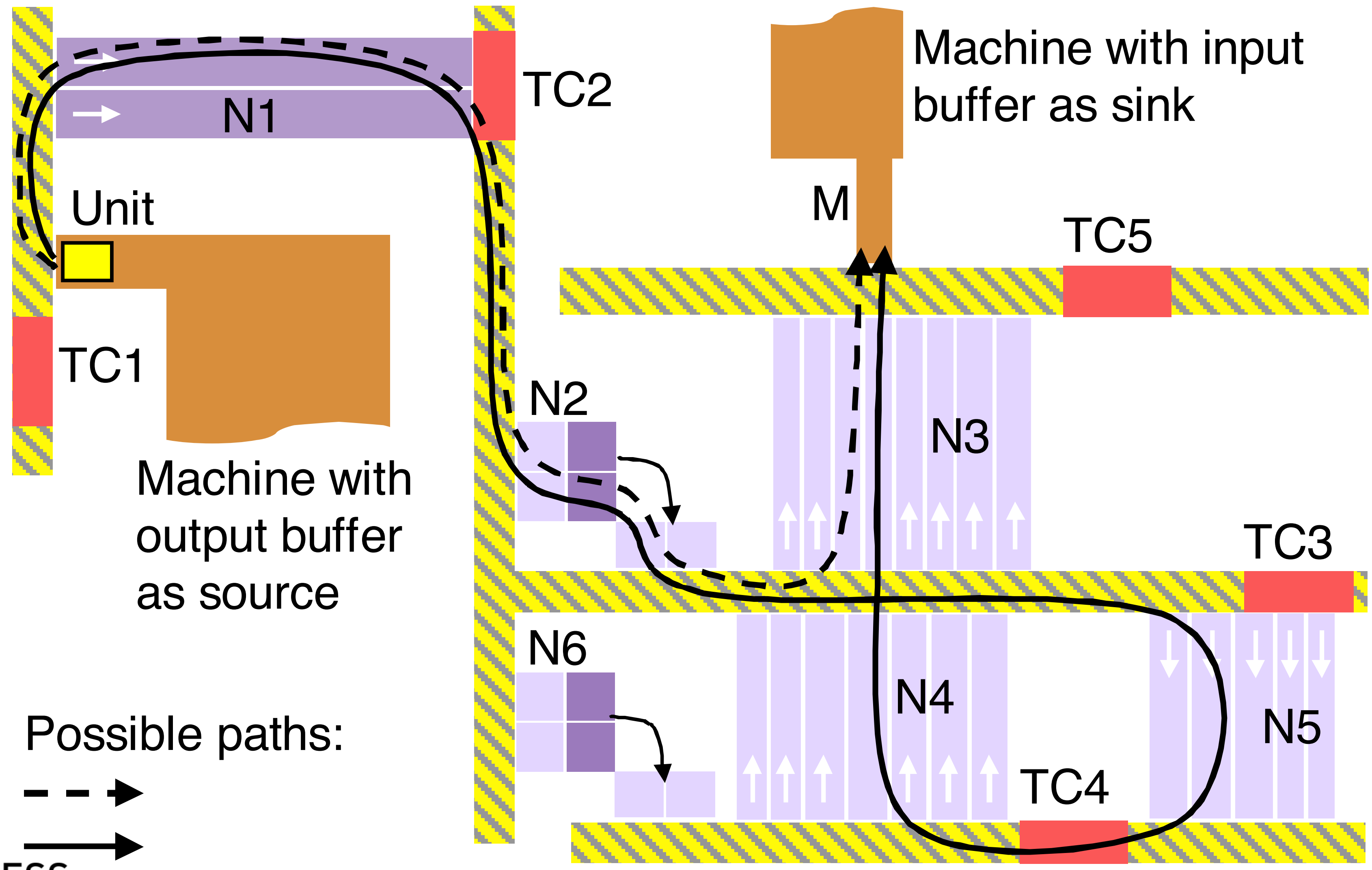
Specification of Information Flows and Interaction Rules

A unit enters the lane	It decides to exit the lane	It sends a request for a transfer car	The unit exits the lane

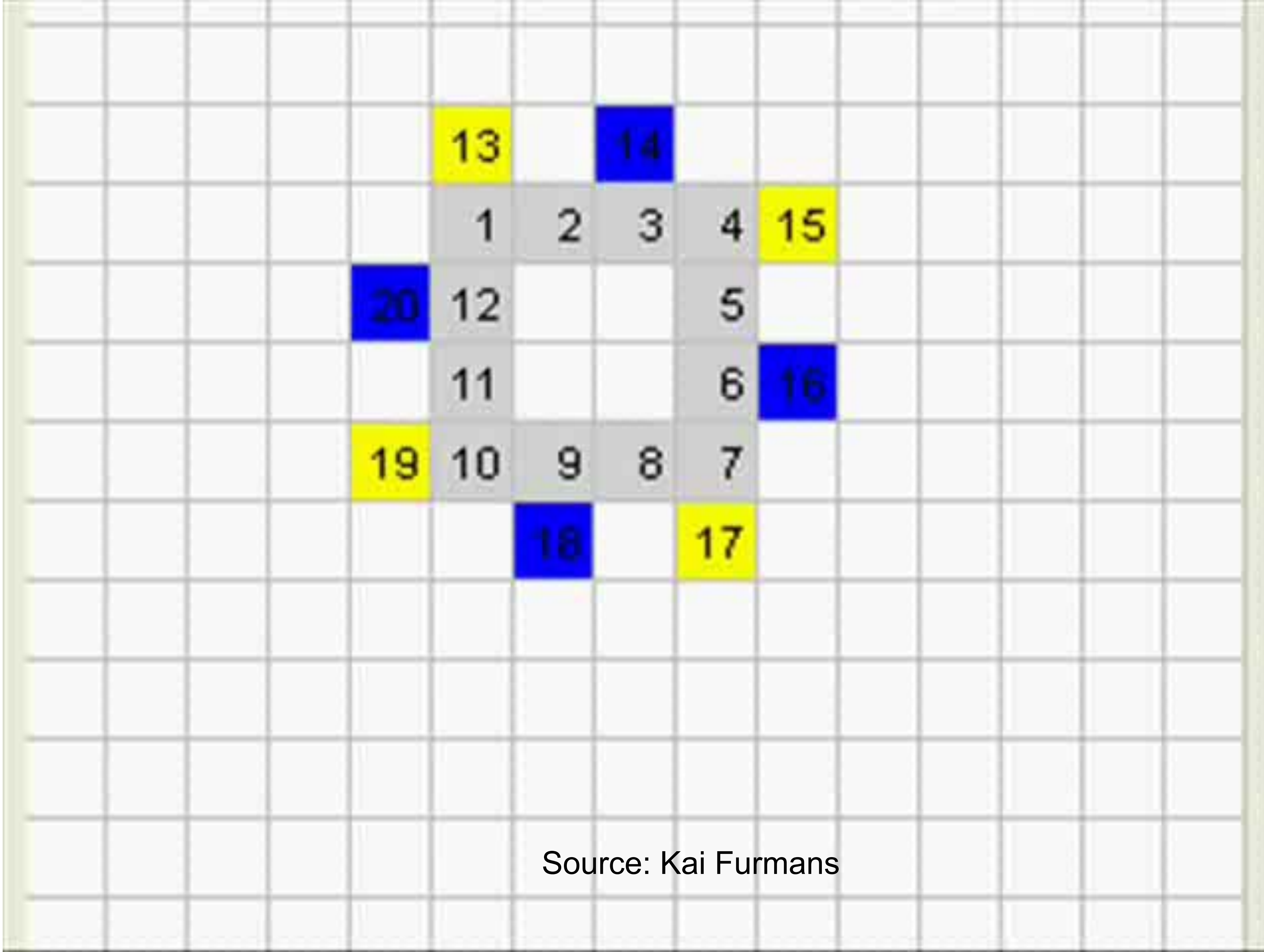


ETH zürich

Alternative Paths: Interaction-Based Routing



Possible paths:



Source: Kai Furmans

A New Paradigm

Universe – C. Flammarion, Woodcut, Paris 1888, Colorit : Heikenwaelder Hugo, Vienna 1998, CC BY-SA 2.5

Over-Regulation

Supporting Desirable and Efficient Behavior

Self-Organizing Traffic Flow

Pedestrian, Crowd, and Evacuation Dynamics

Dirk Helbing

with Anders Johansson, Wenjian Yu, Mehdi Moussaid,

Illes Farkas, Peter Molnar, Tamas Vicsek and others

Lane Formation in Pedestrian Counterflows

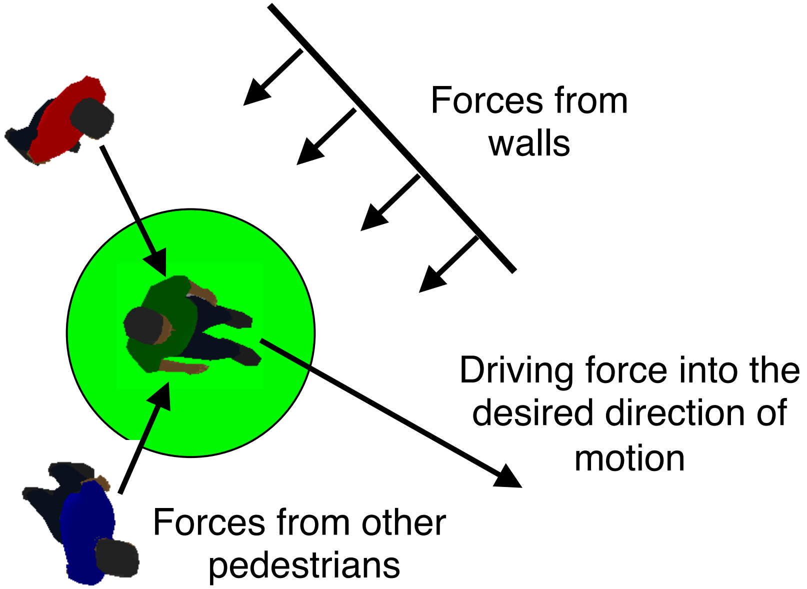
The Social Force Model

The social force model assumes individual goals (to reach a certain destination efficiently), social interactions (e.g. avoidance of collisions), and institutional setting (e.g. walls).

$$\frac{dx_\alpha}{dt} = v_\alpha(t) \quad \text{(equation of motion)}$$

$$\underbrace{\frac{dv_\alpha}{dt}}_{\text{acceleration}} = \underbrace{\frac{1}{\tau_\alpha}(v_\alpha^0 e_\alpha^0 - v_\alpha)}_{\text{driving force}} + \underbrace{\sum_{\beta(\neq\alpha)} F_{\alpha\beta}^{\text{int}}}_{\text{interactions}} + \underbrace{F_\alpha^{\text{walls}}}_{\text{boundaries}}$$

(acceleration equation)



Experimental Study of Individual Avoidance Behavior

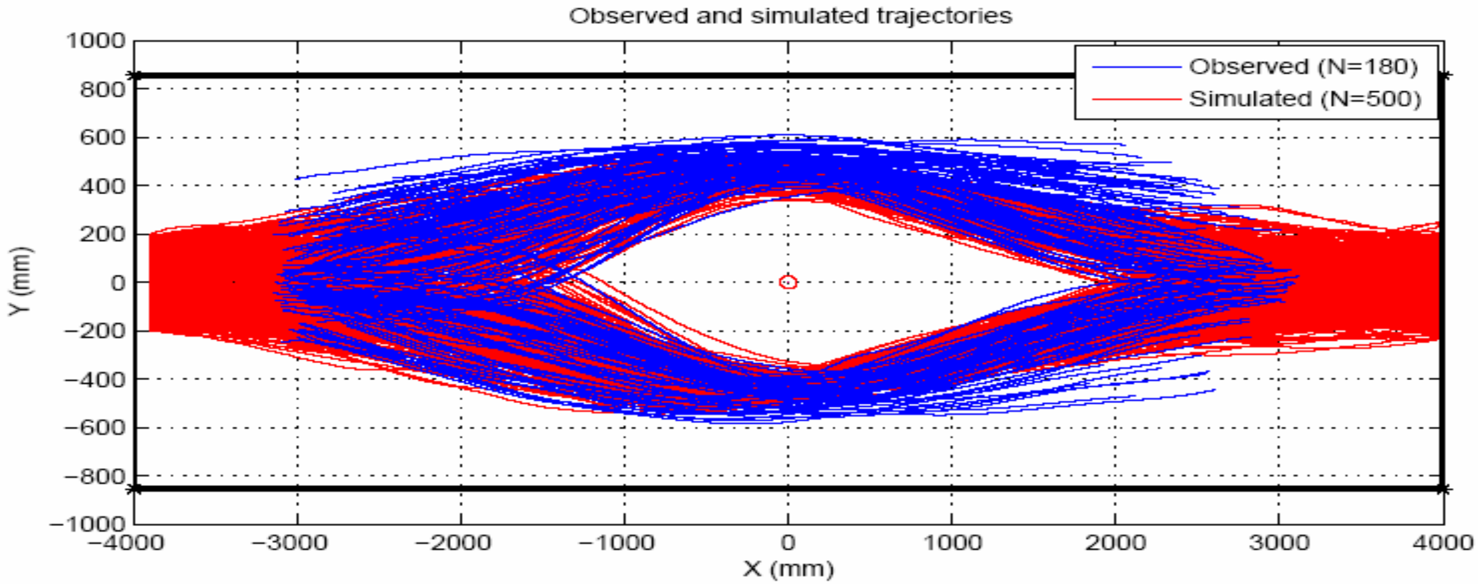
Avoidance of a static pedestrian

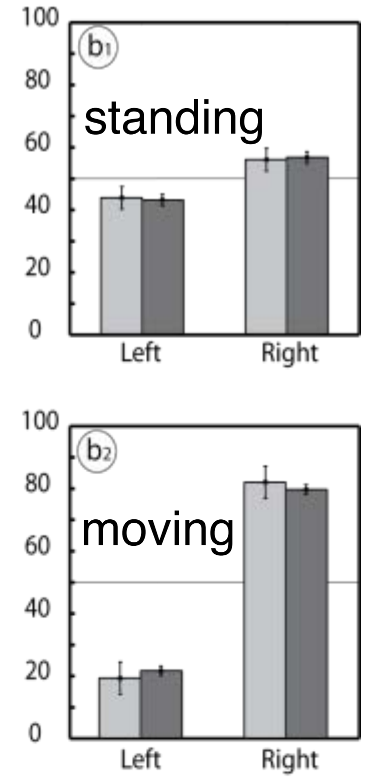
Avoidance of a moving pedestrian

Validation 1: Corridor Experiment

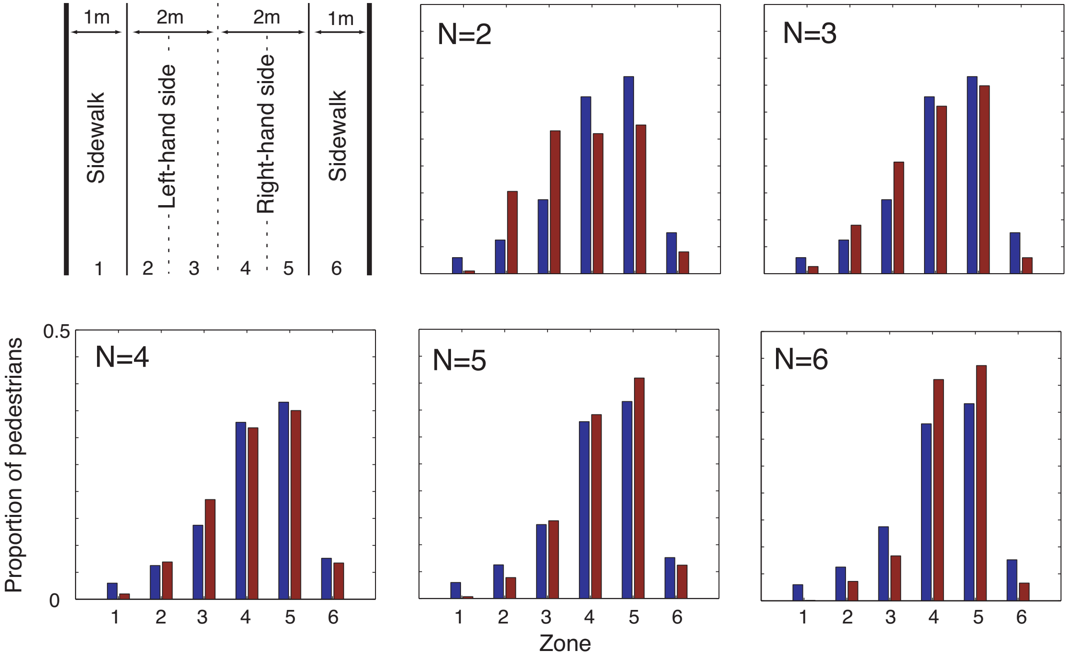
preferred avoidance side

Observed and simulated pedestrian trajectories



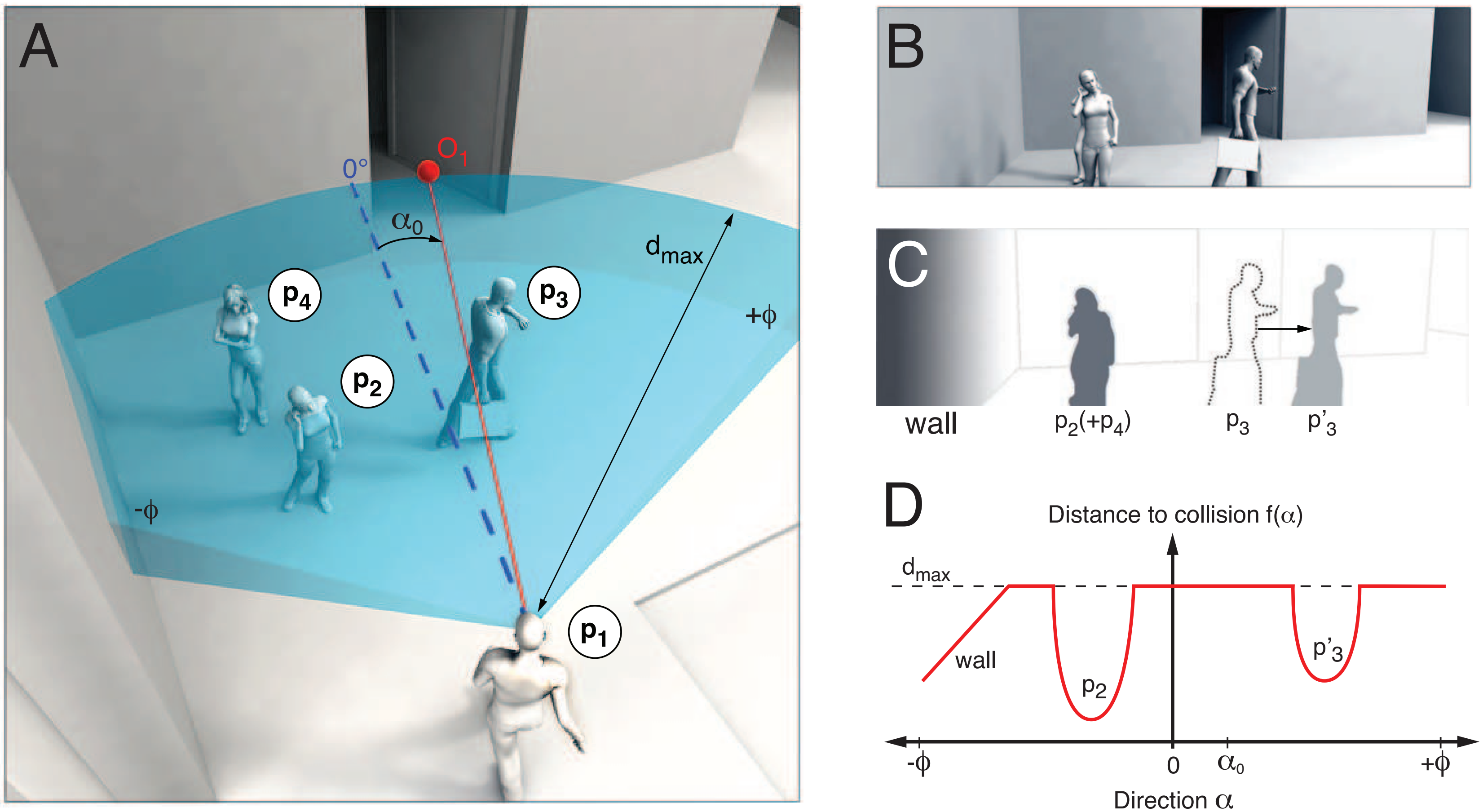


Validation 2: Collective Dynamics



Observations in a crowded street

Visualization of the Cognitive (Heuristics) Model

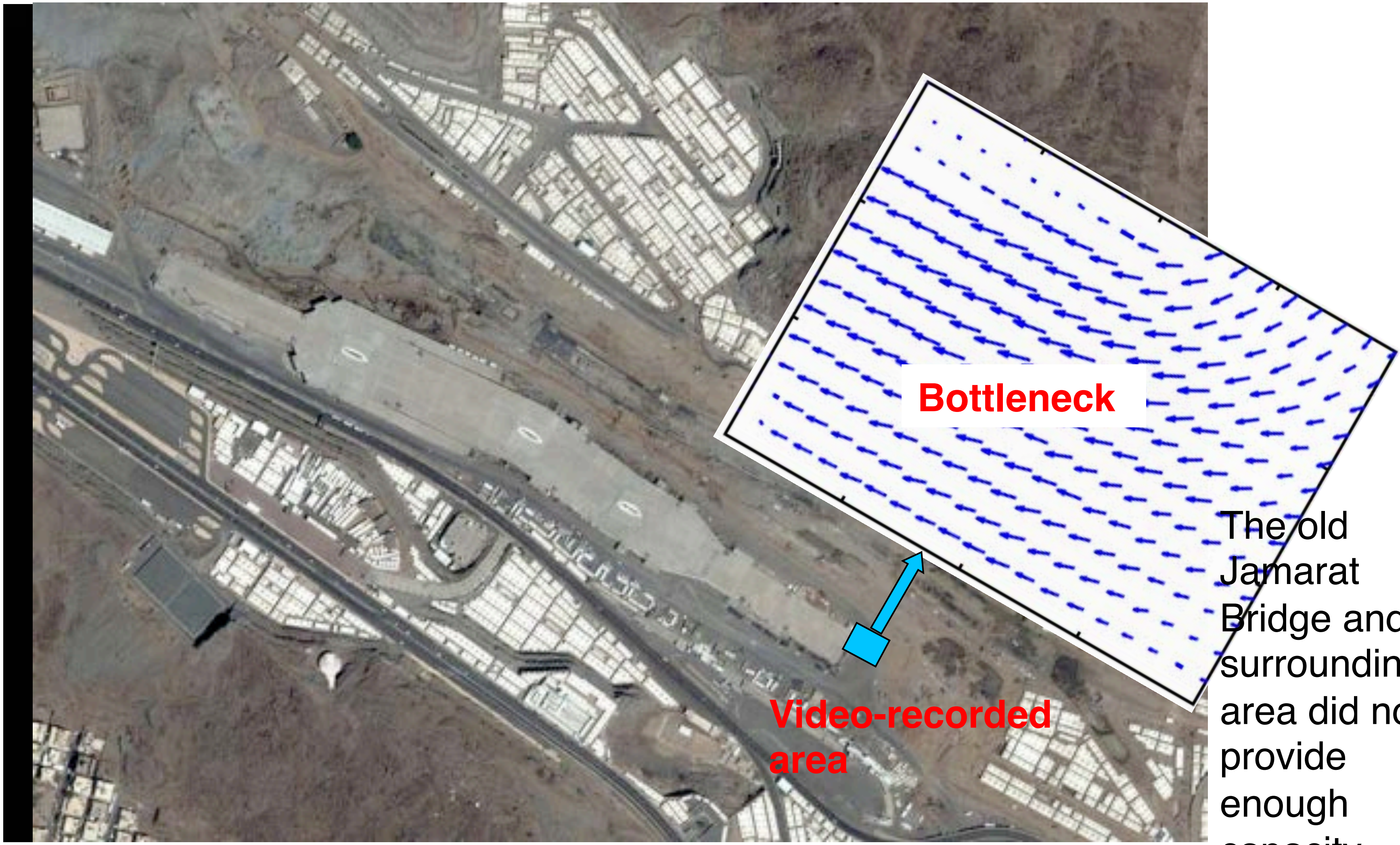


M. Moussaid et al, in PNAS

1. Walk into the least obstructed direction (“hunt for gaps”)
2. Adjust speed to keep time headway constant

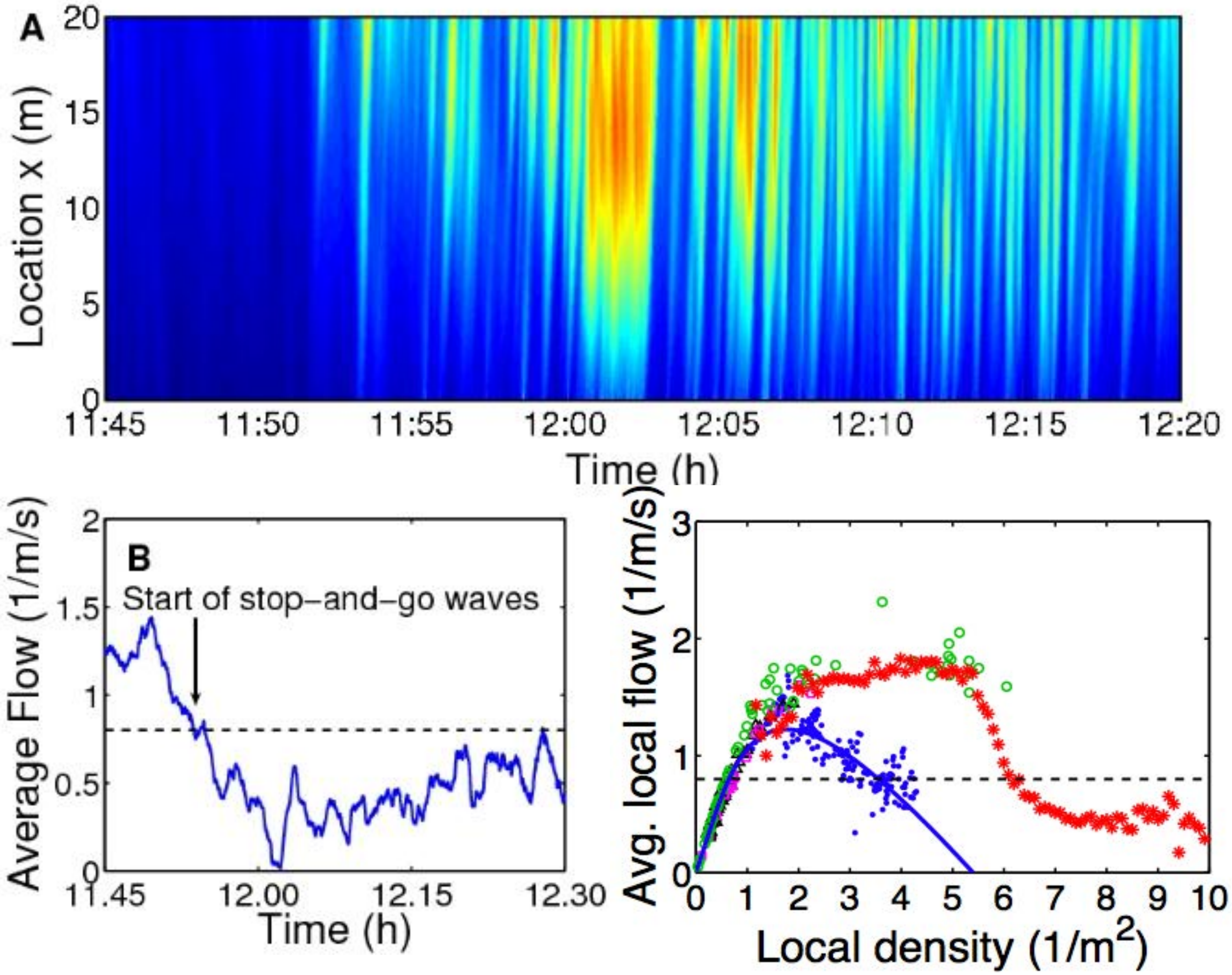
PTV VisWalk Planning Software

The Jamarat Bridge (as of January 2006)



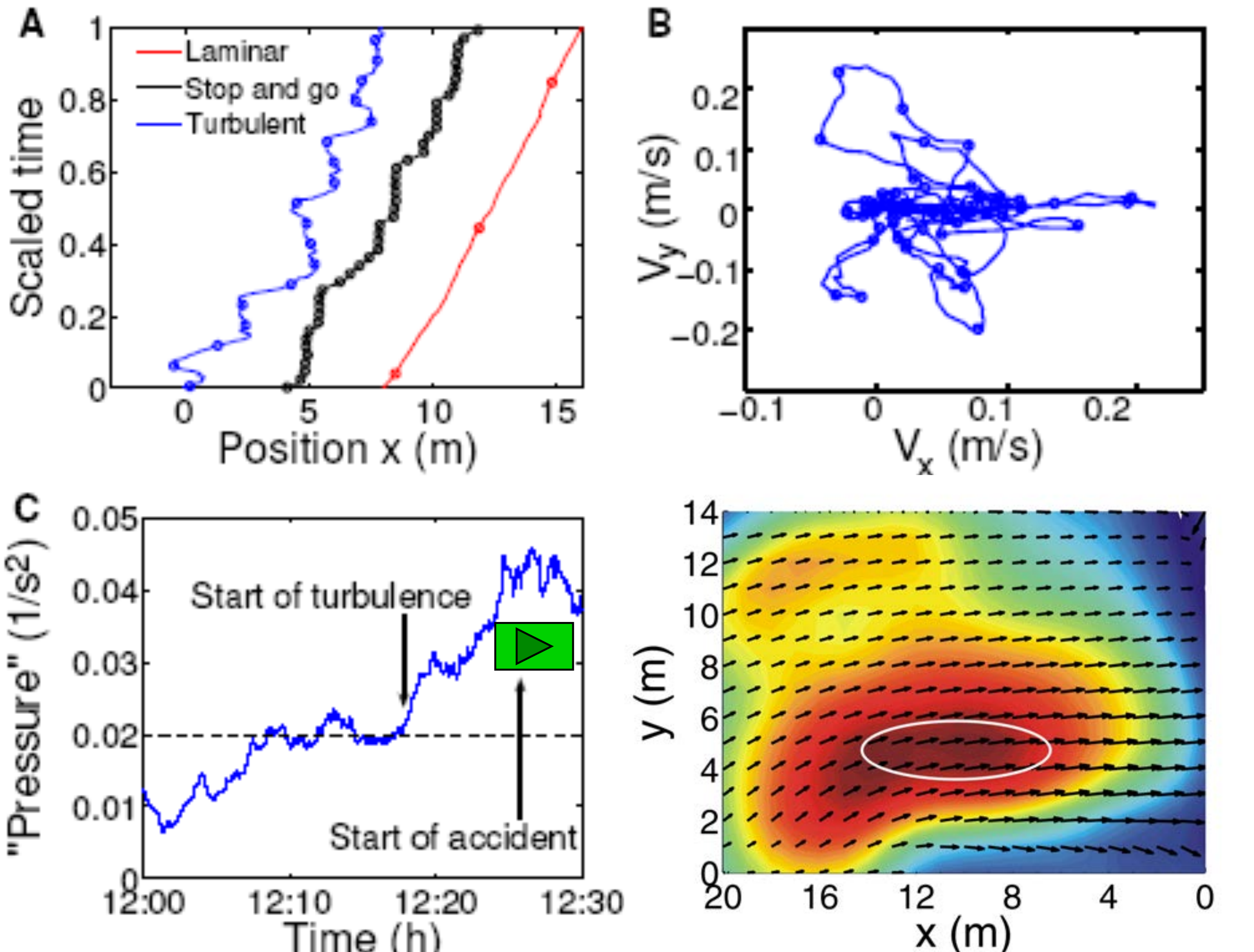
The old Jamarat Bridge and surrounding area did not provide enough capacity anymore

Transition from Smooth to Stop-and-Go Flow



Mechanism is very different from stop-and-go waves in vehicle traffic!

Transition from Stop-and-Go Flow to "Crowd Turbulence"



The density times the variation in speeds constitutes the hazard! Pressure fluctuations cause turbulent motion and potentially the falling and trampling of people.

Increased driving forces occur in crowded areas when trying to gain space, particularly during "crowd panic"

Crowd Turbulence as Final Cause of the Love Parade Disaster

Crowd Safety by Information Feedback

ETH zürich

Building a Planetary Nervous System for Real-Time Measurements

Dirk Helbing and team

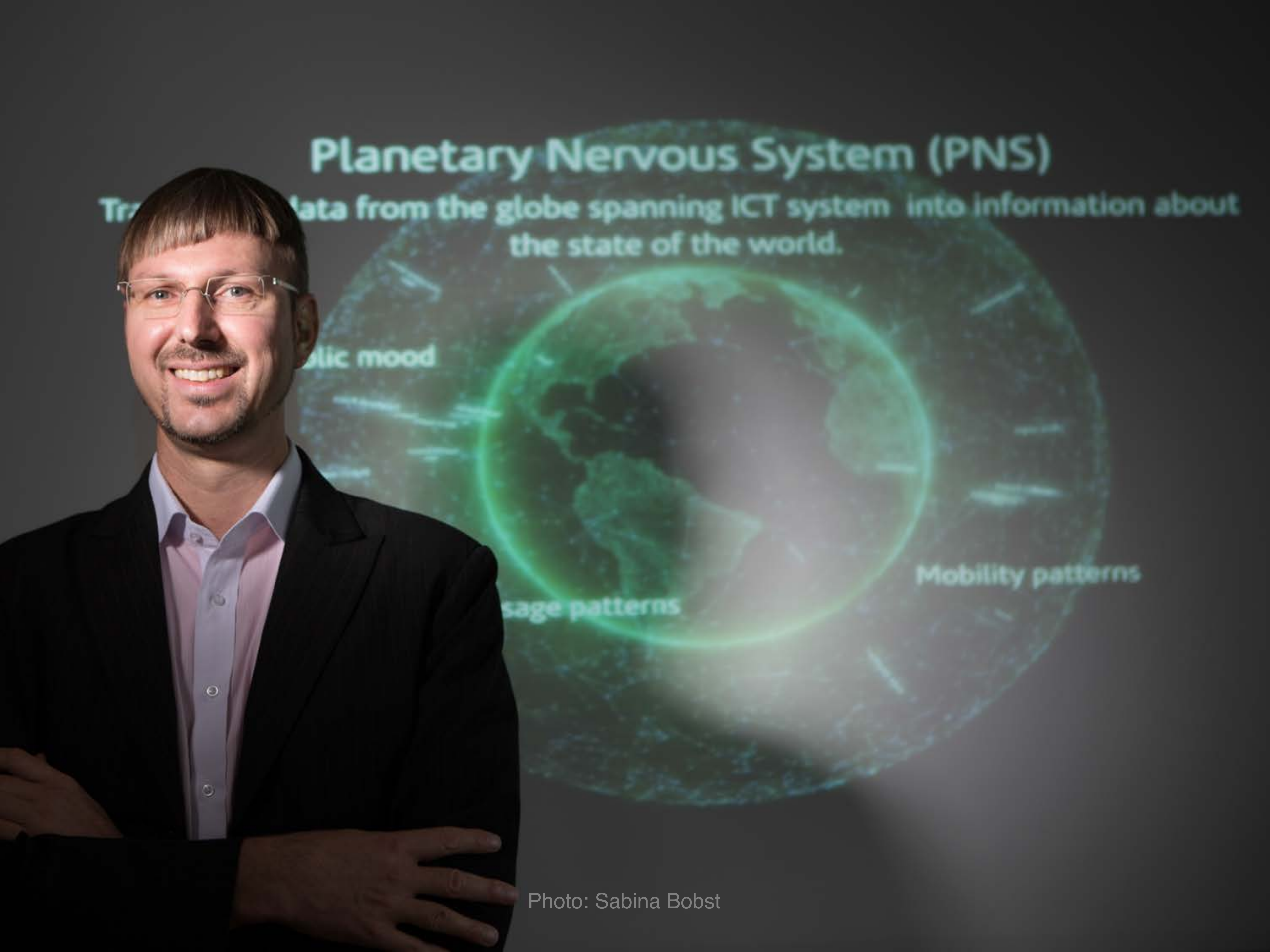


Photo: Sabina Bobst

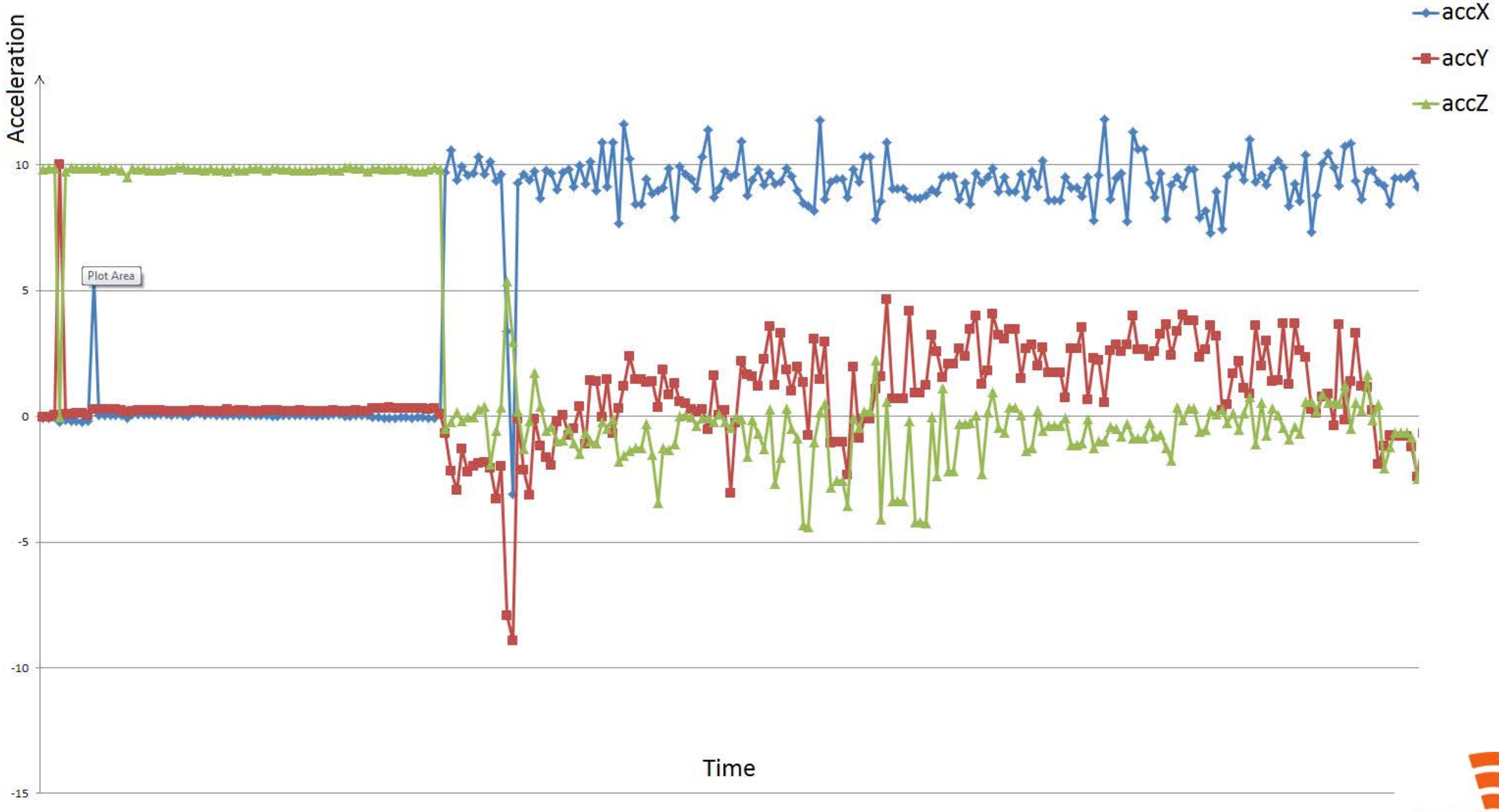
All It Takes is You and Your Smartphone

Source: http://mashable.com/2012/12/13/smartphone-holiday-wishlist/

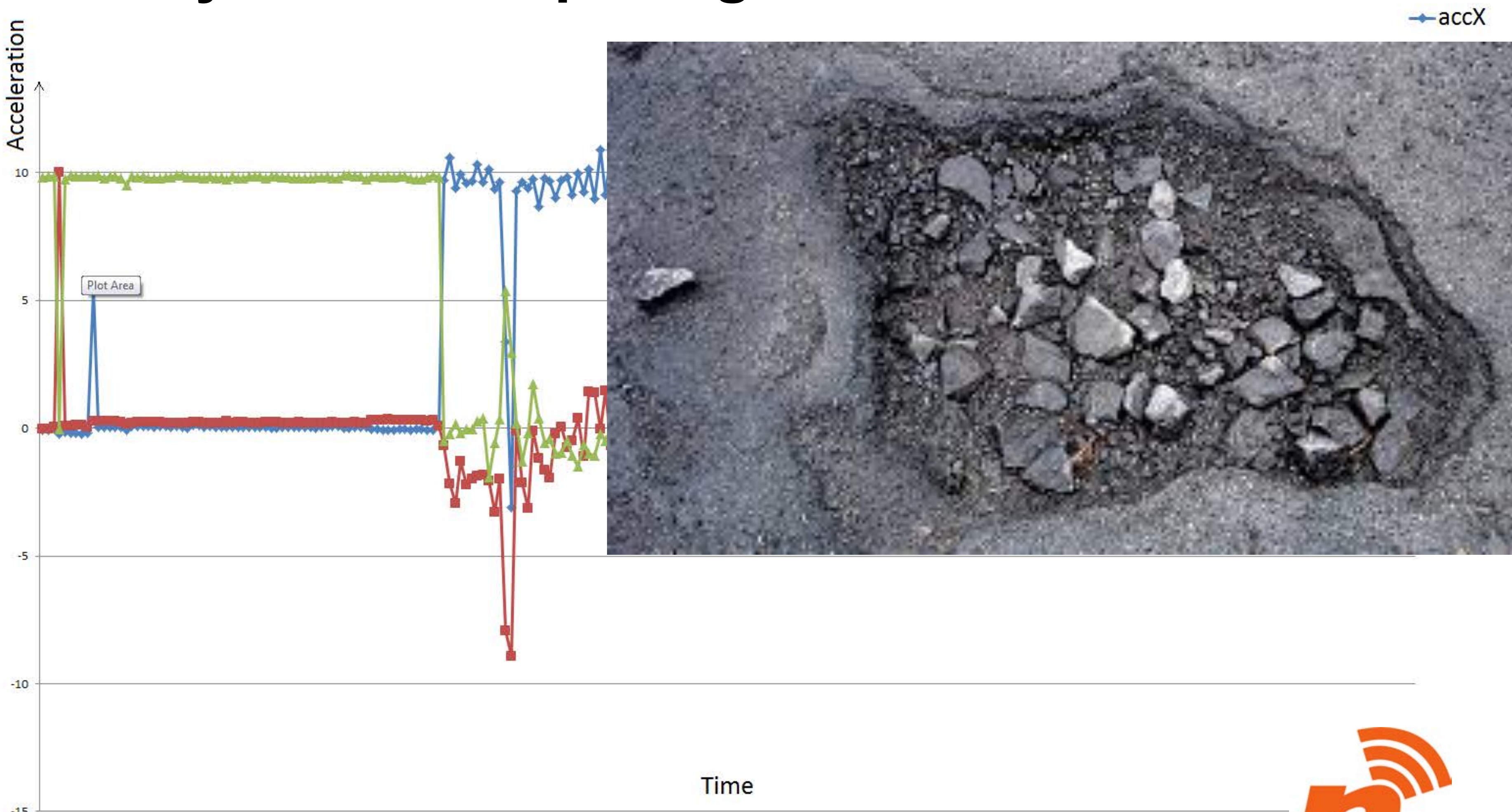
Because We Can Connect Smartphones to Build a Global Measurement System

ETH zürich

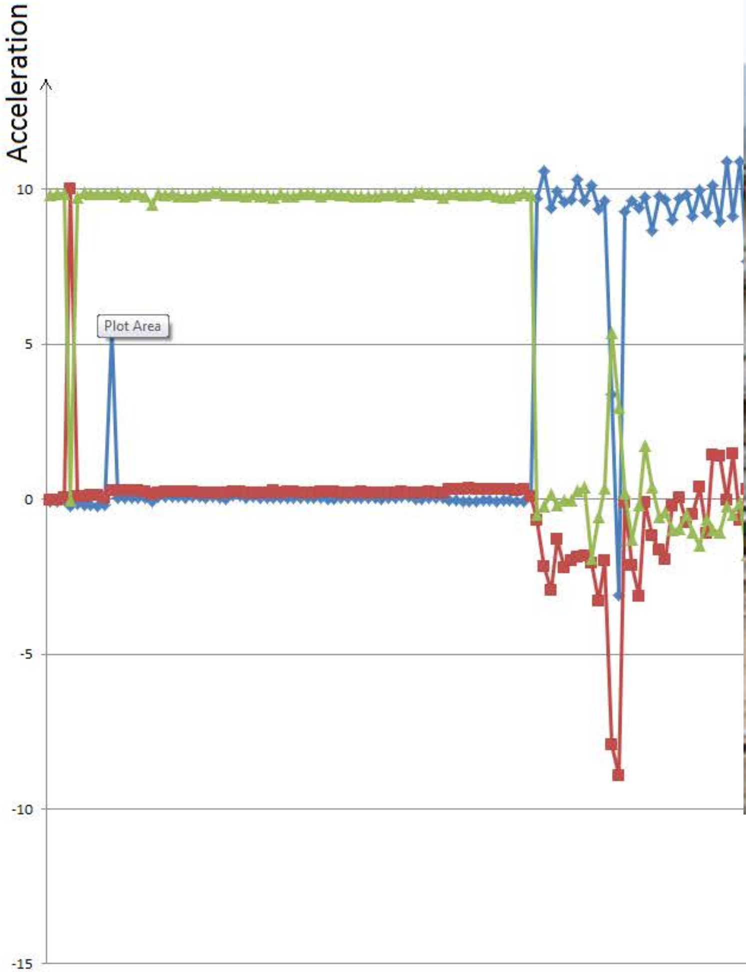
Visualization of Acceleration Data



Identify Road Bumps Together

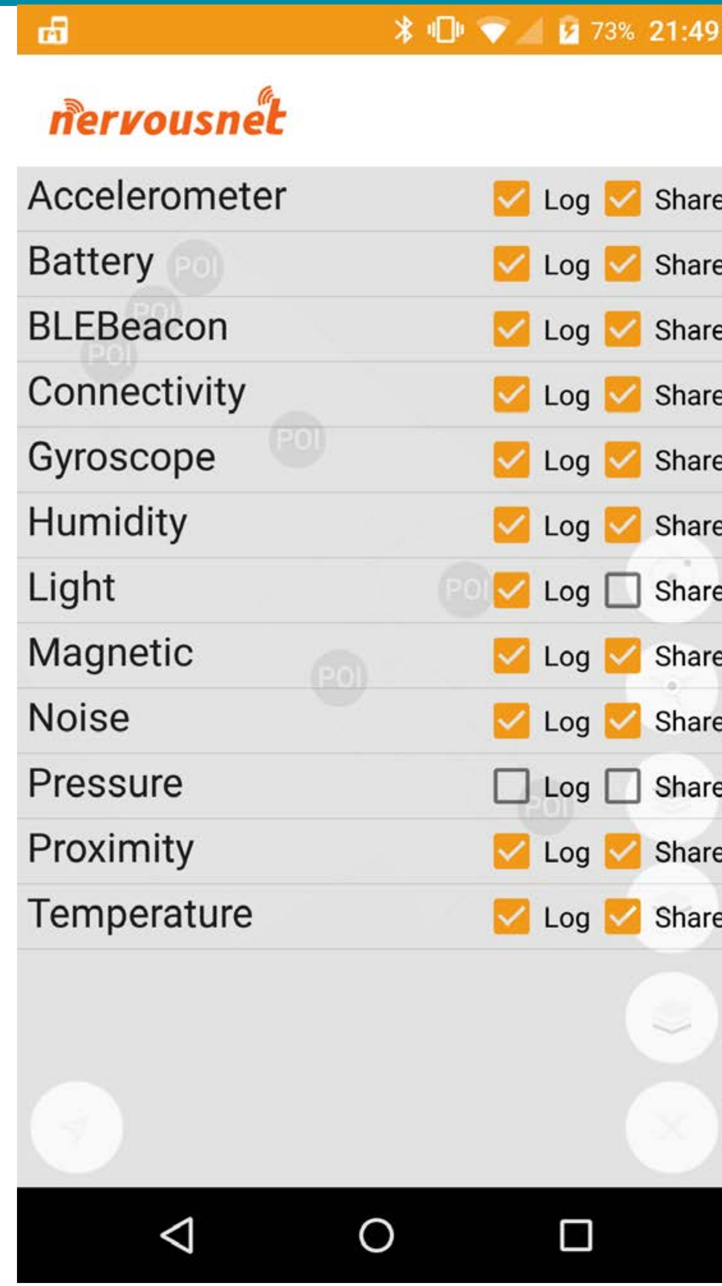


Detect Earthquakes and Warn Our Friends

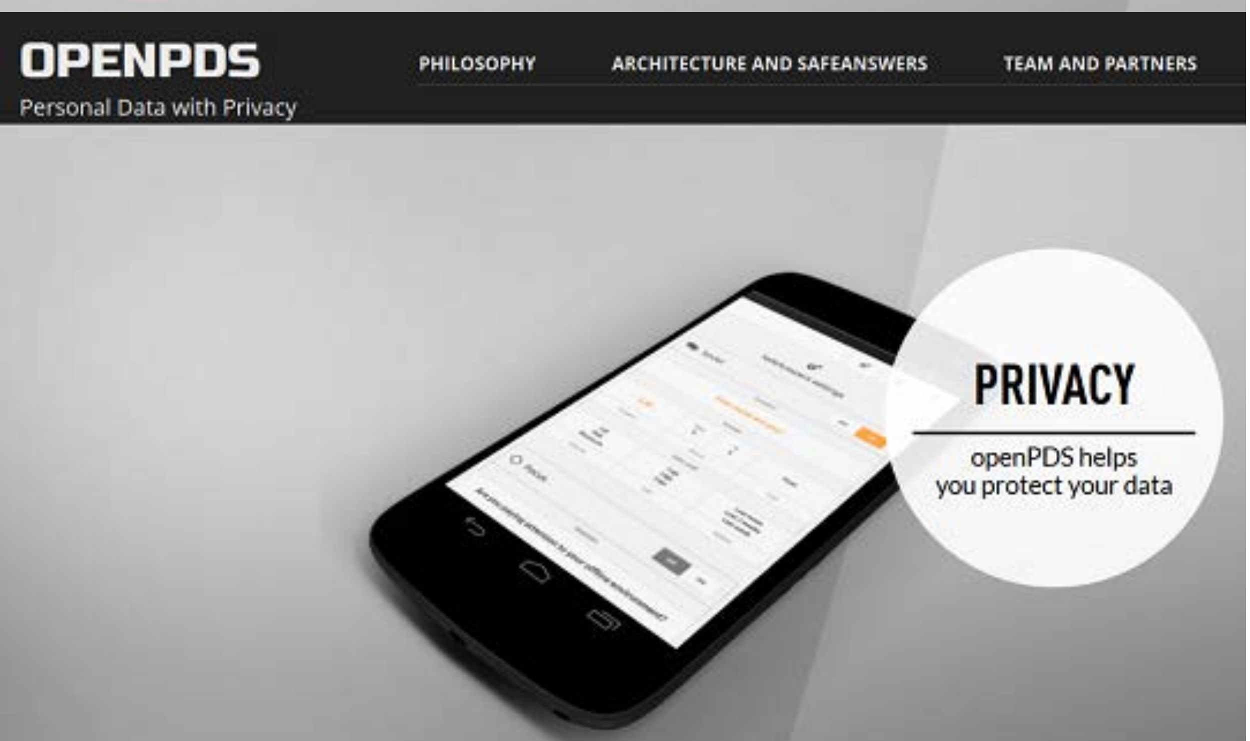


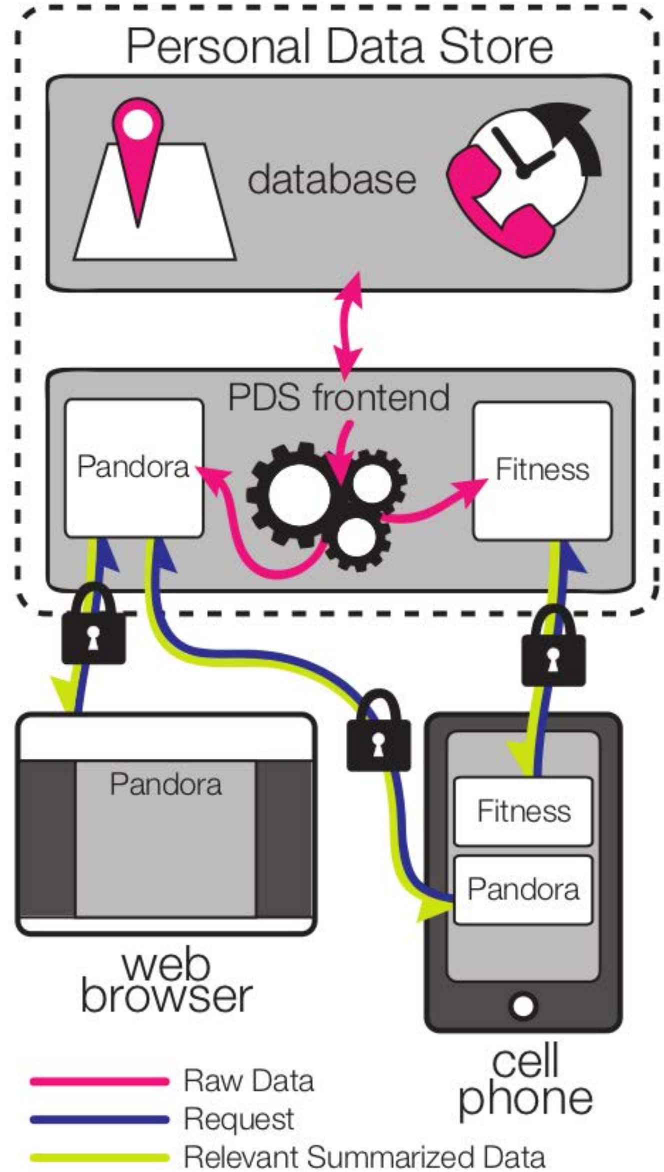

But We Need A System We Can Trust …

An Information System Controlled by You!



Privacy and Data Ownership





The „Internet of Things“ as Citizen Web

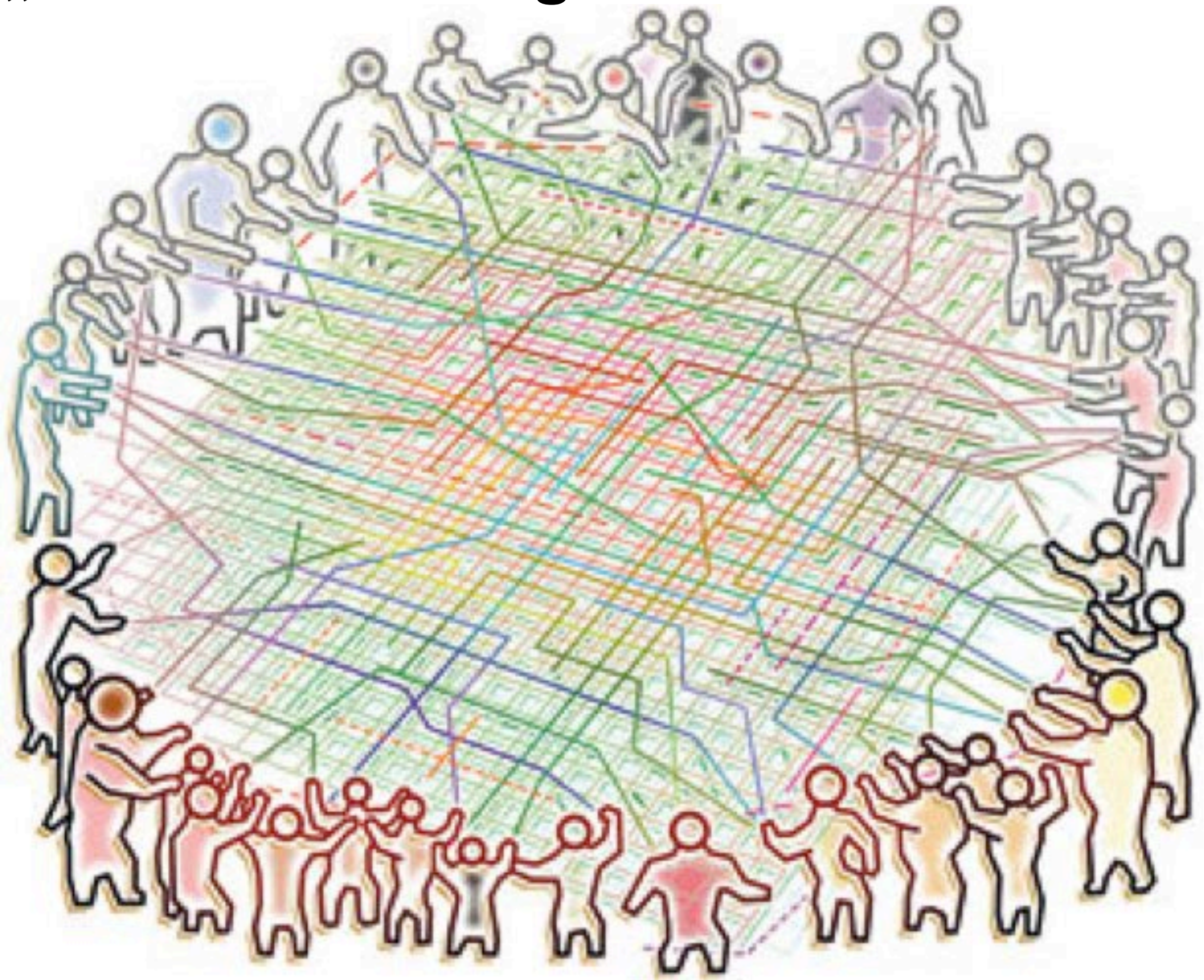
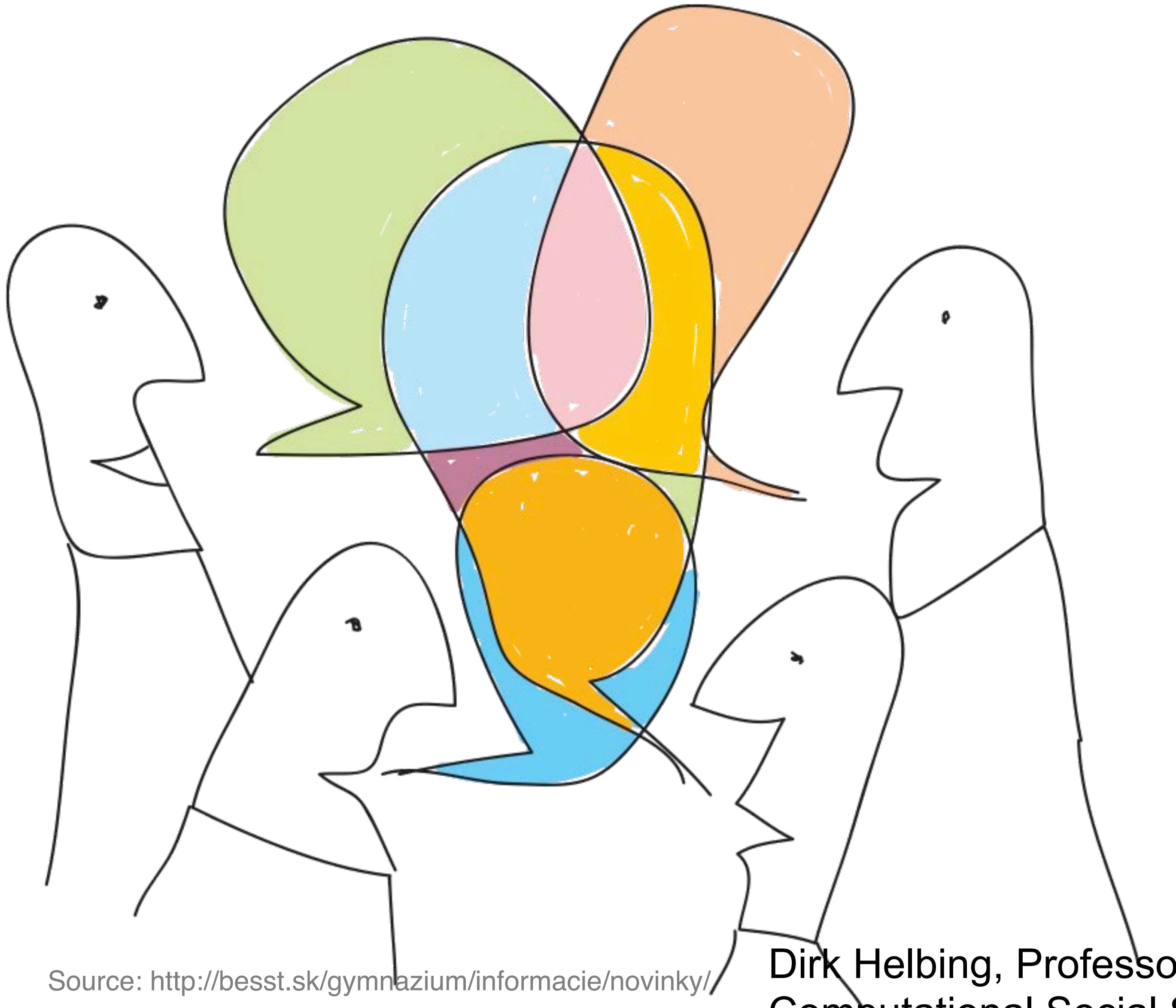


Illustration:Jac Depczyk, http://www.thisviewoflife.com/index.php/magazine/articles/climate-change-and-inter-group-cooperation

A Participatory System



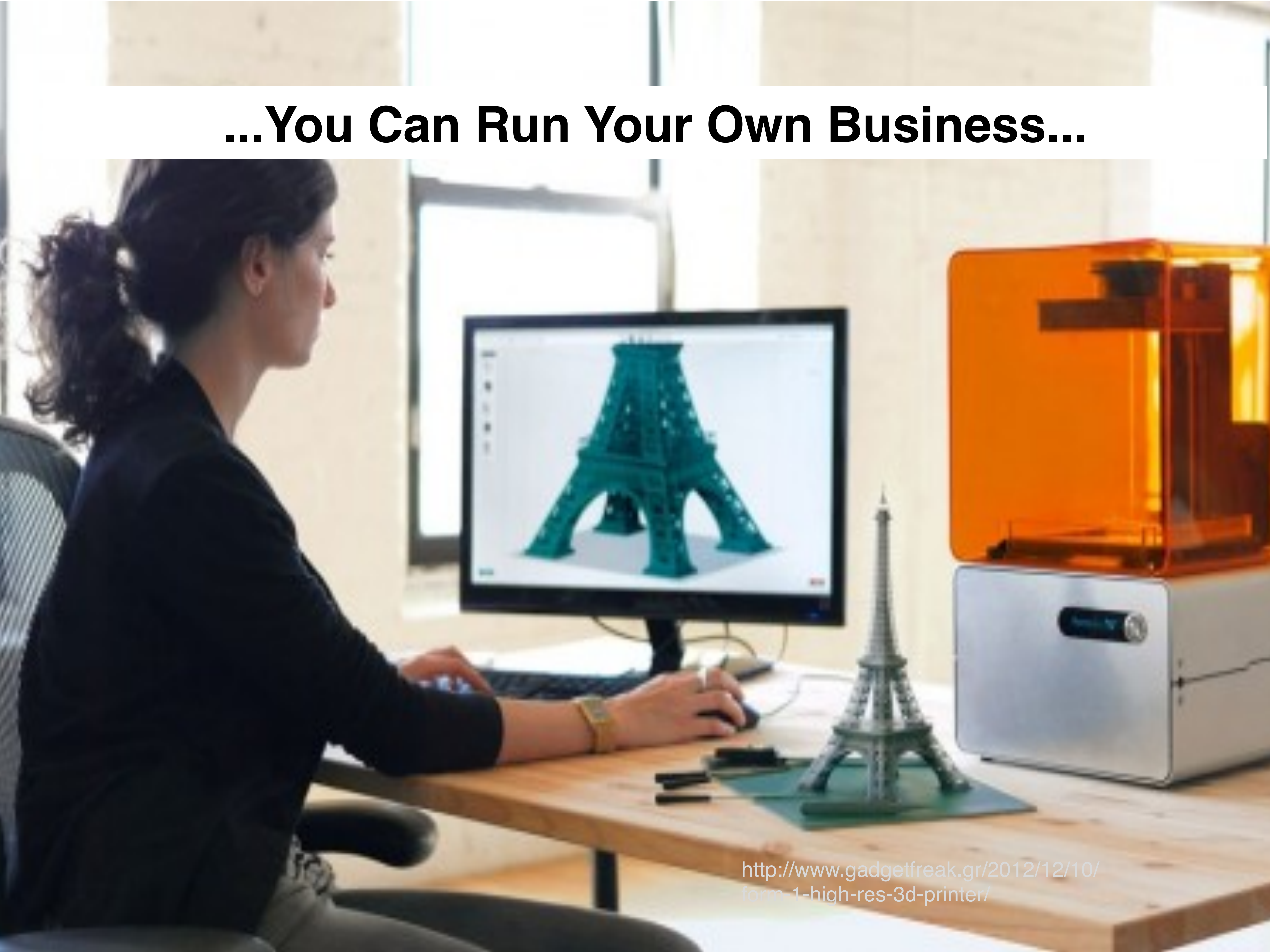
Source: http://besst.sk/gymnazium/informacie/novinky/

An Open Data Source, but Real Time

With A Micro-Payment System...

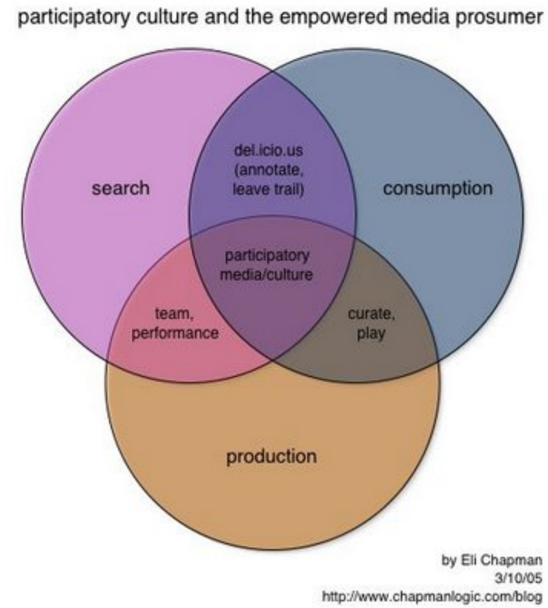
http://www.europaeum.org/europaeum/?q=node/533

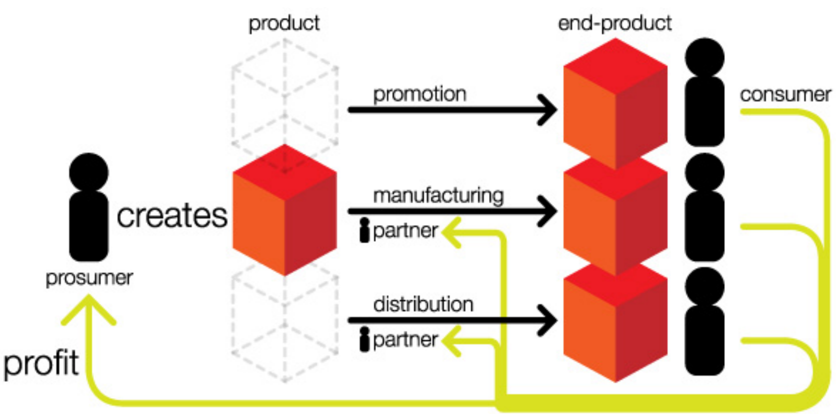
...You Can Run Your Own Business...

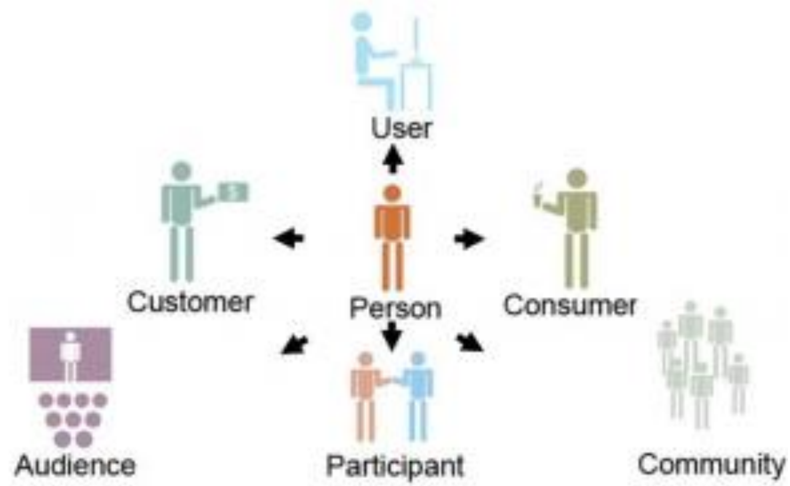


http://www.gadgetfreak.gr/2012/12/10/form-1-high-res-3d-printer/

… and Collaborate with Others







Let‘s Do This Together!

Image Source: http://demosite.in/applicationdevelopment.php

Create Our Own Open Data

"Give and take is fair play."

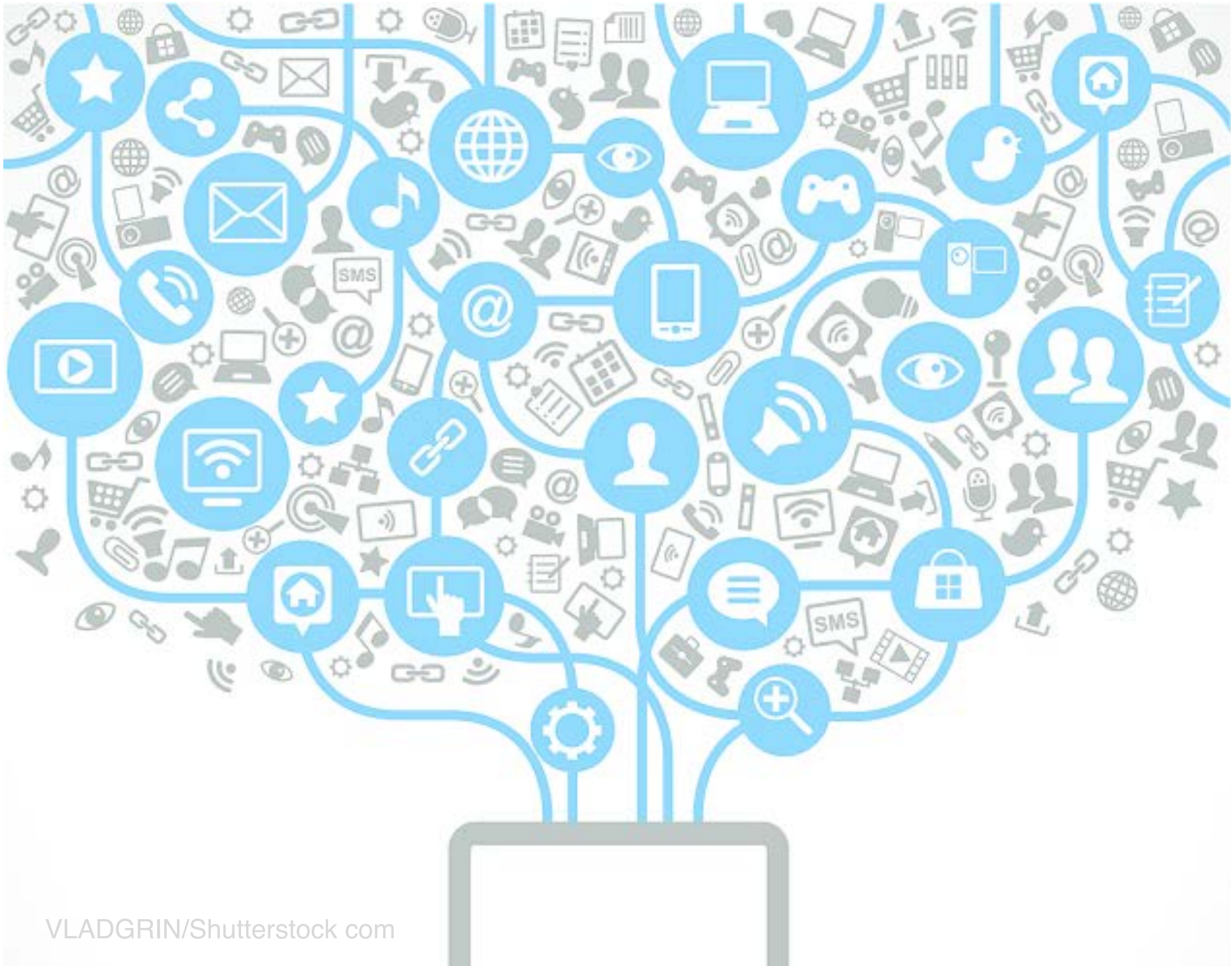
English Proverb

Source www.quotescover.com

Share Source Codes

http://it.com.mk/github-napolni-5-godini-i-ima-3-5-milioni-korisnitsi-i-6-milioni-repozitoriumi/github/

Grow a Powerful Information and Innovation (Eco-)System Together ...

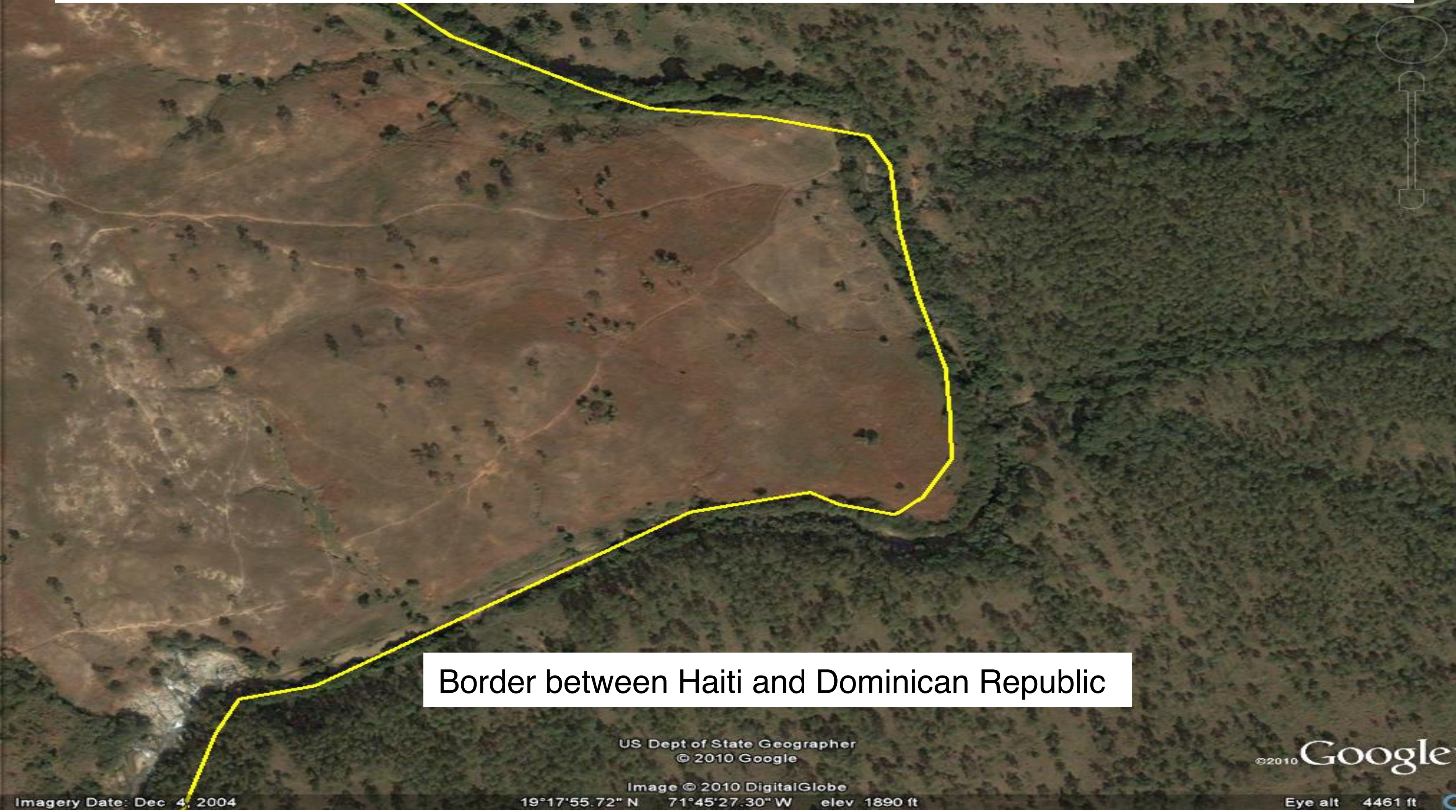


… and Create New Opportunities for Everyone

www.enableeurope.eu

The nervousnet startup team, @ ETH Zurich

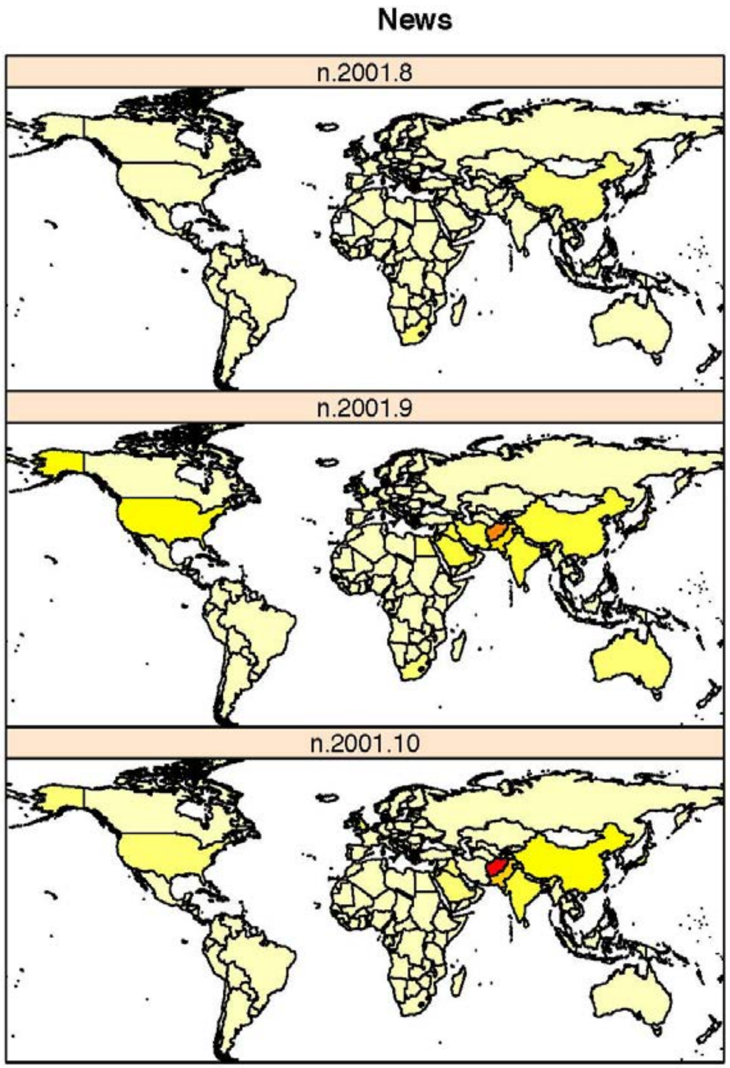
Map Environmental Change and Who Causes It

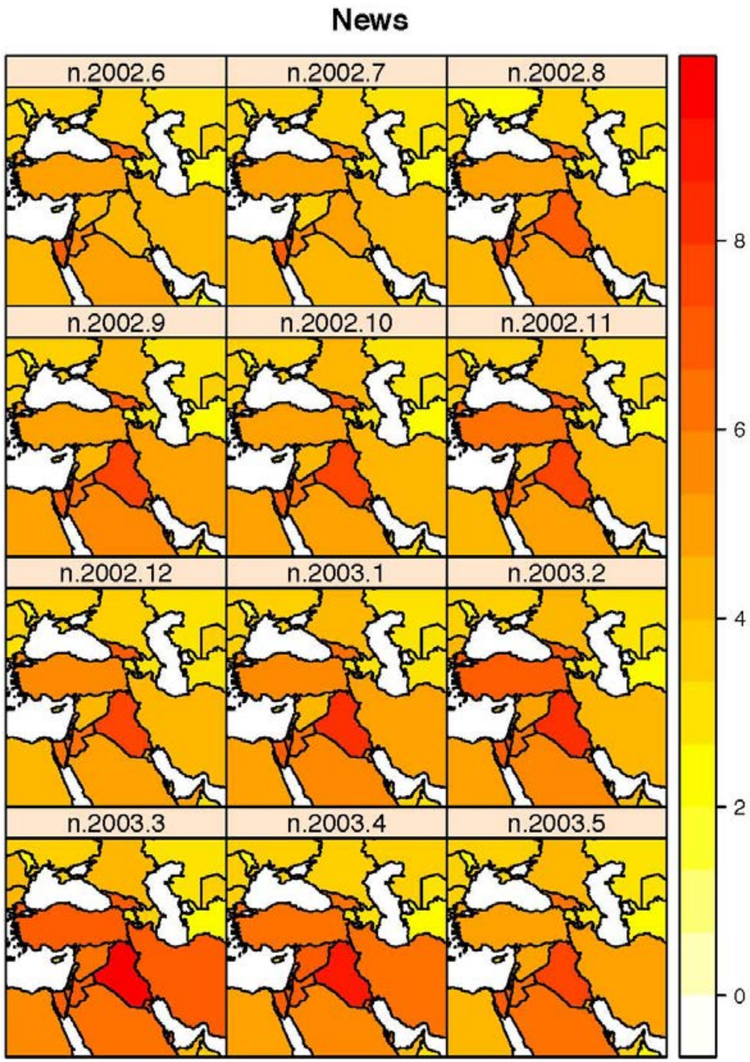


Map Resources and Who Uses Them

Would help to avoid shortages and recessions

Map Conflicts and How They Come About





Joint work of Thomas Chadefaux and Dirk Helbing

Get Ready!

https://ampaipse.wordpress.com/page/2/

Team Up With Your Friends + Colleagues

Join the *nervousnet* Community

nervousnet

nervousnet@ethz.ch