ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Complex Traffic Dynamics on Freeways

Prof. Dr. rer. nat. Dirk Helbing

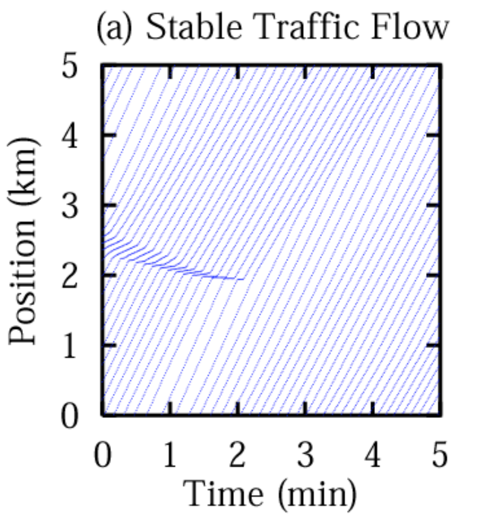
Chair of Sociology, in particular of Modeling and Simulation

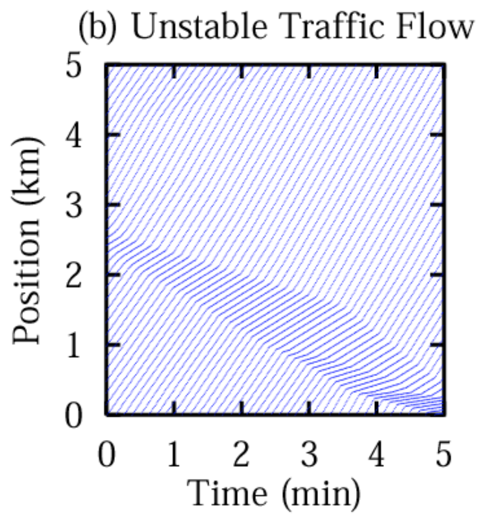
www.soms.ethz.ch

with Anders Johansson, Martin Treiber, Arne Kesting,

Stefan Lämmer, Martin Schönhof, and others

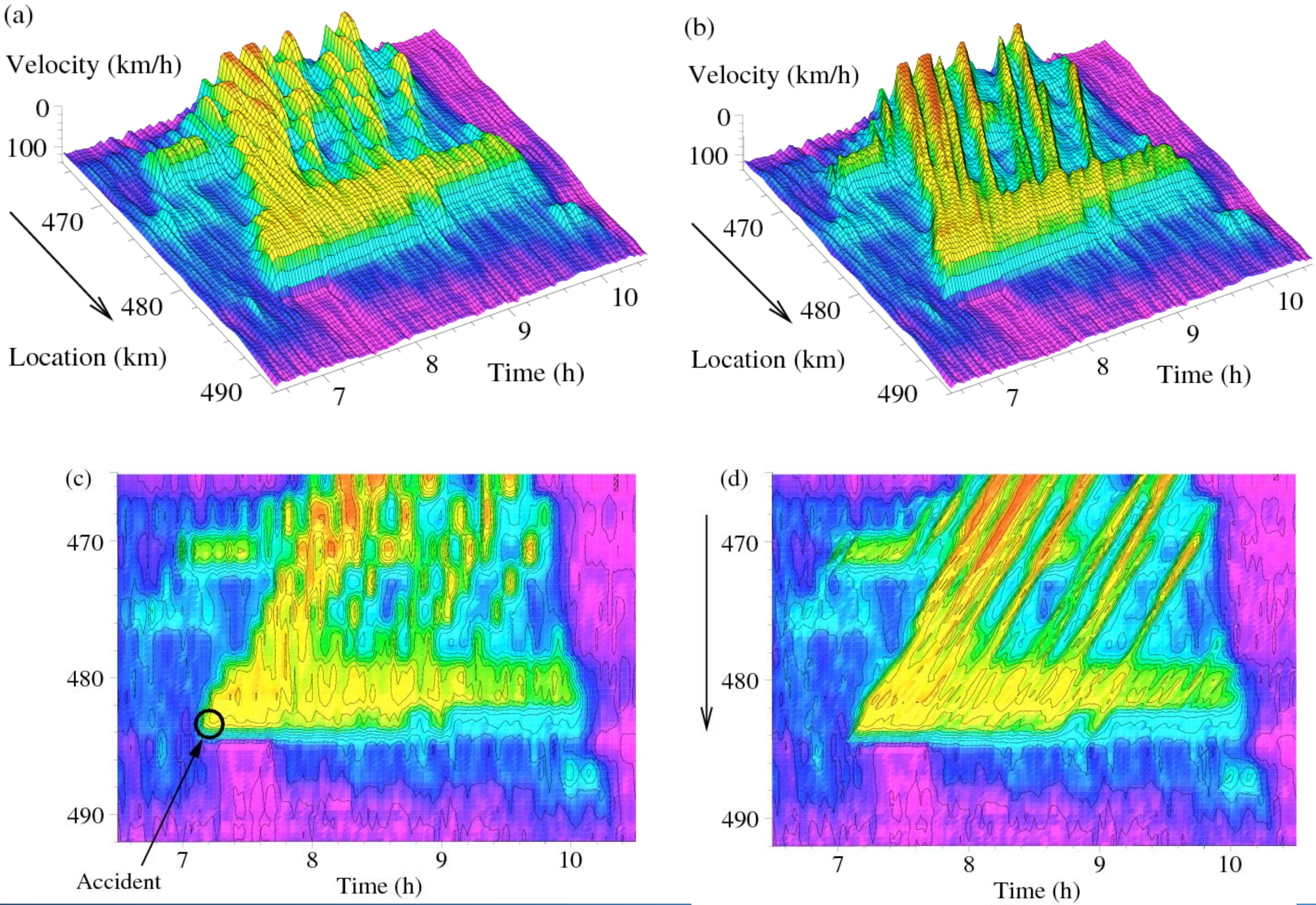
Instability of Traffic Flow



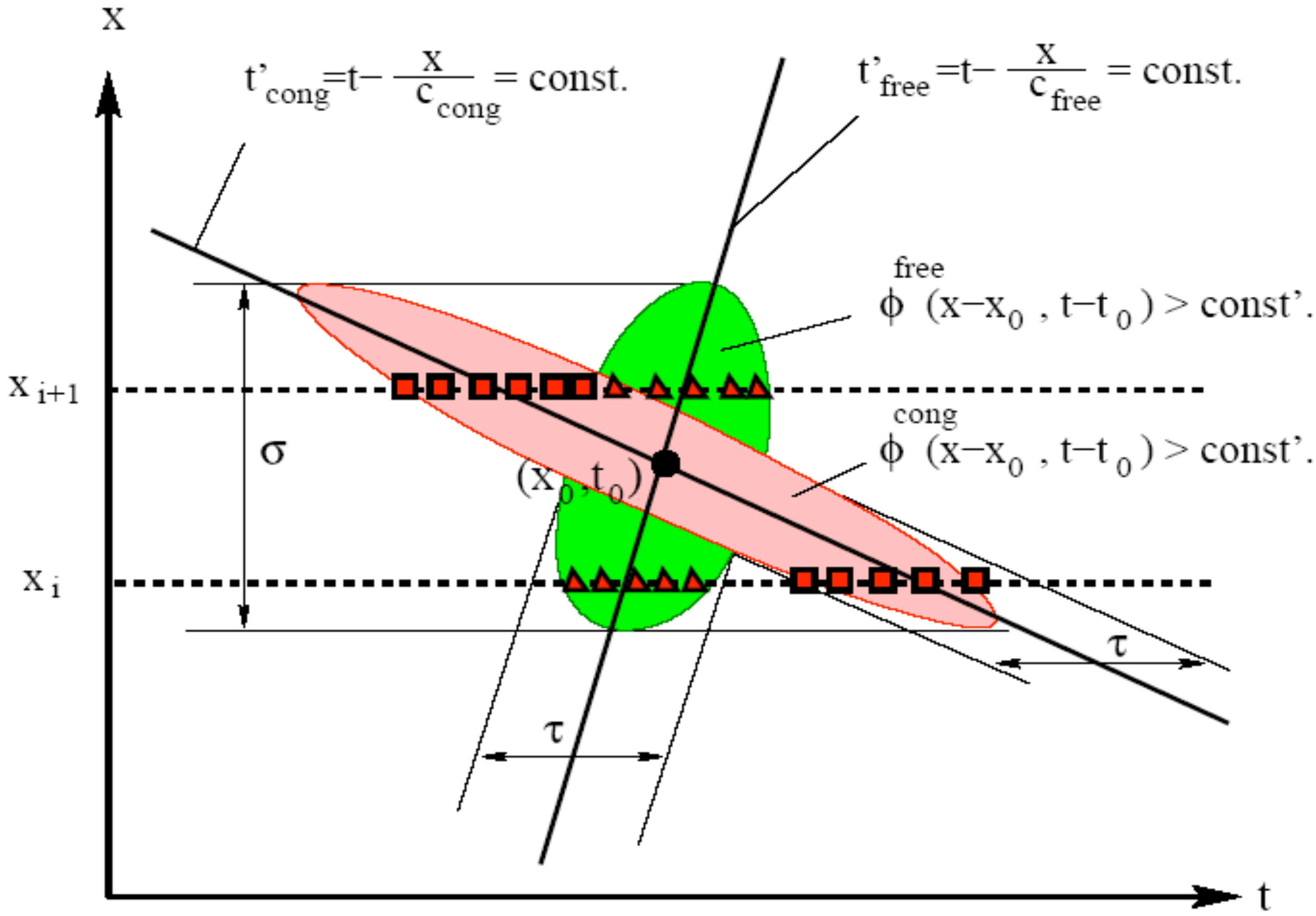


Source: Sugiyama et al.

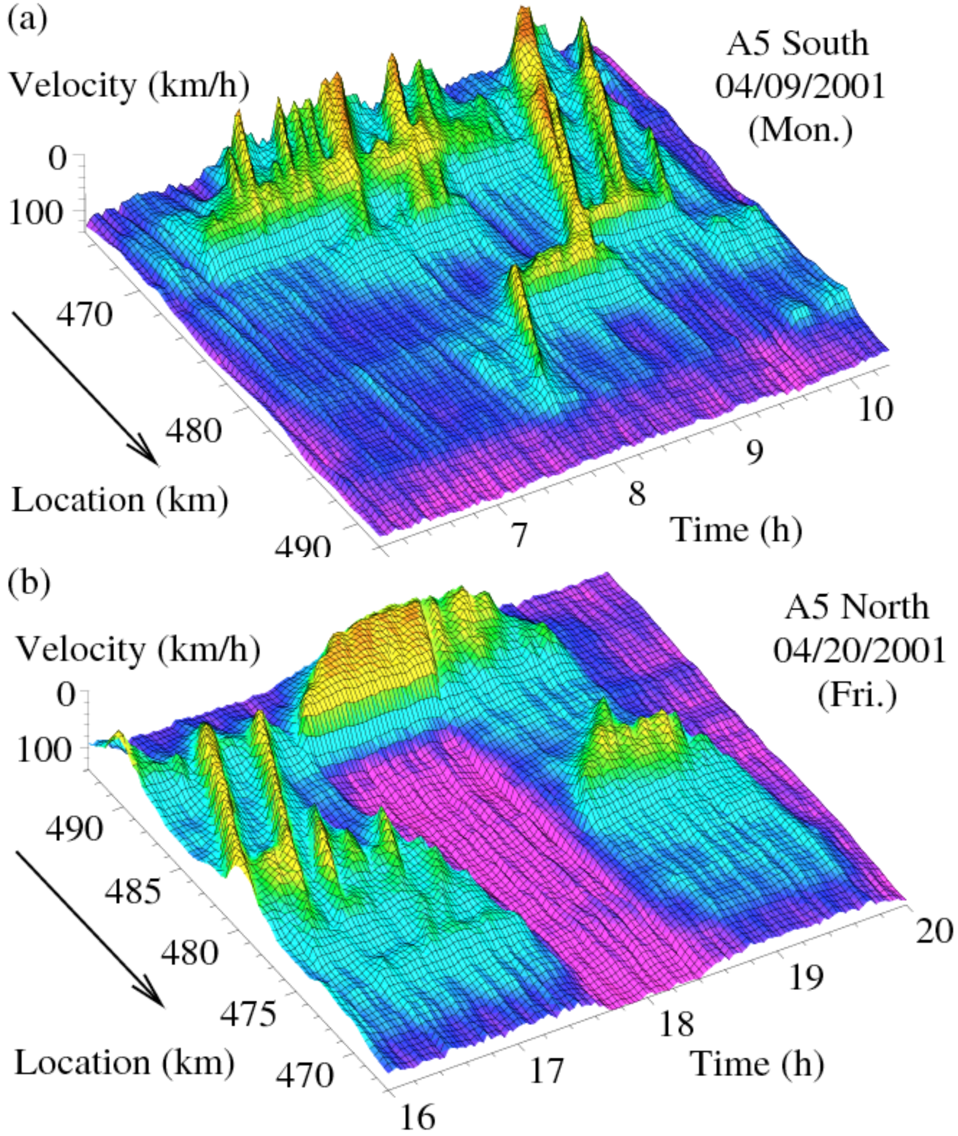
How to Analyze the Cross-Sectional Traffic Data



How the Adaptive Smoothing Method Works



Complex Congestion Patterns

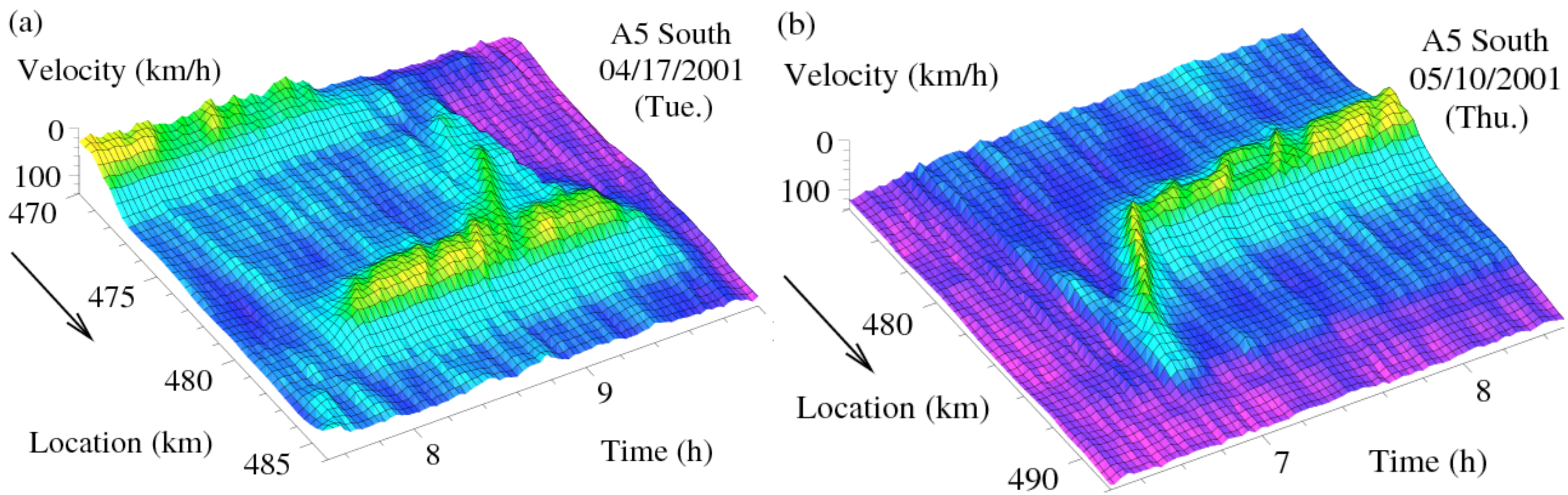


The boomerang effect triggers a pinned localized cluster, which grows upto the off-ramp. This generates a moving localized cluster, which causes an accident at kilometer 479.2. The off-ramp of Intersection Bad Homburg allows for stop-and-go waves.

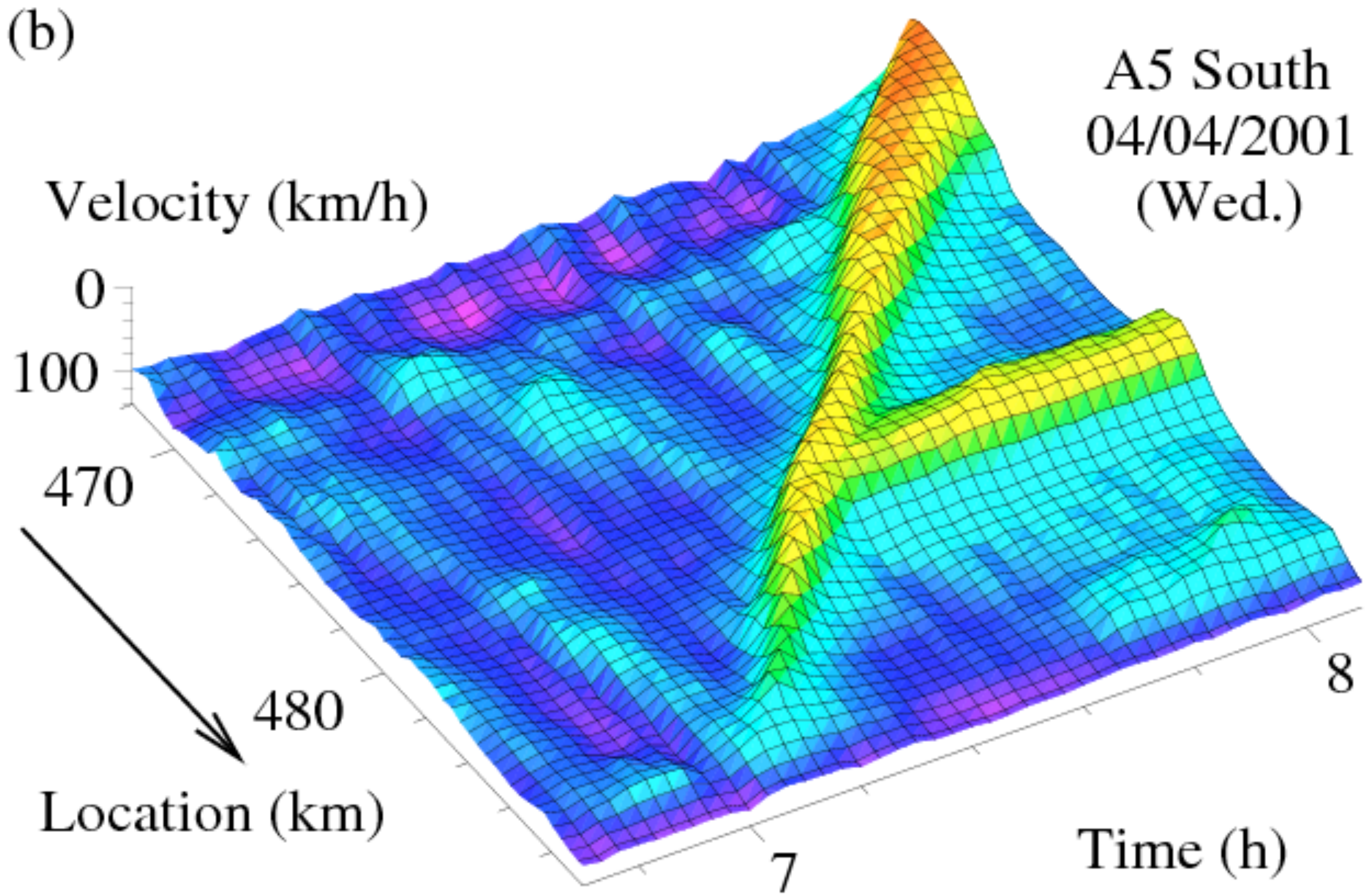
An accident at kilometer 487.5 causes homogeneous congested traffic. After the accident has been cleared, the downstream front moves upstream to Intersection Frankfurt North-West. The off-ramp there mitigates the congestion, resulting in oscillating congested traffic.

Elementary Traffic Patterns: Examples of Pinned Localized Clusters

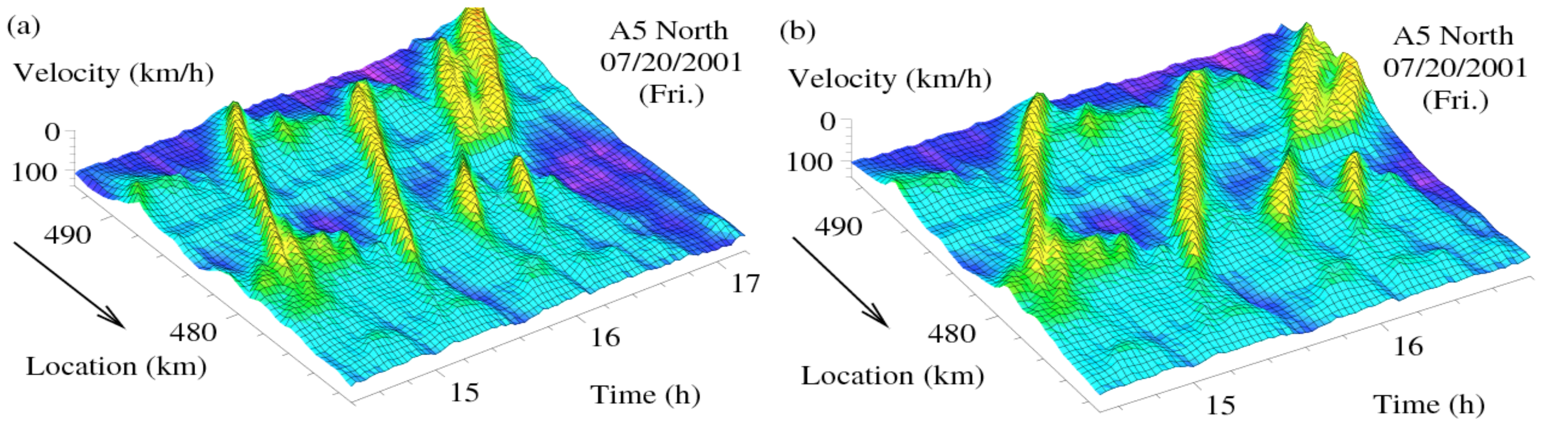
The congested area remains localized as long as it does not reach the upstream end of the off-ramp.



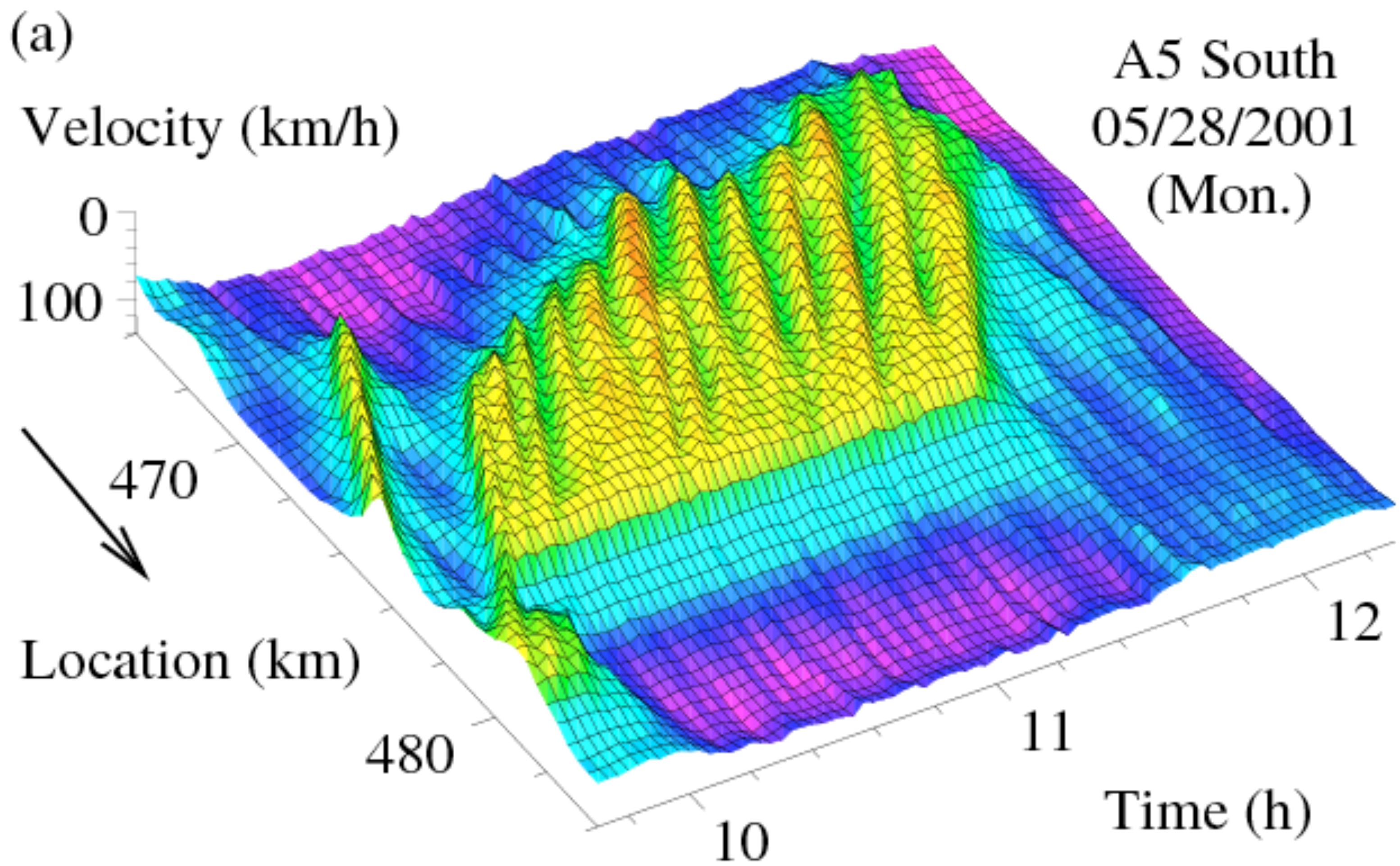
Elementary Traffic Patterns: Example of a Moving Localized Cluster



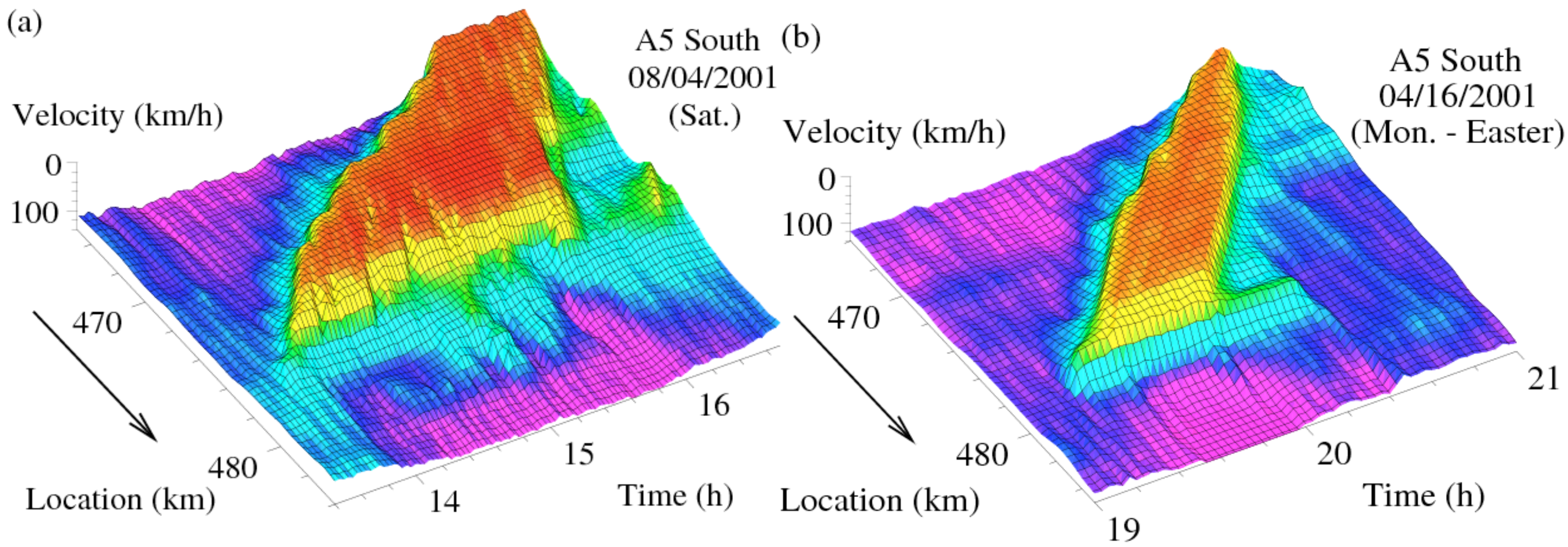
Elementary Traffic Patterns: Examples of Stop-and-Go Waves



Elementary Traffic Patterns: Oscillating Congested Traffic

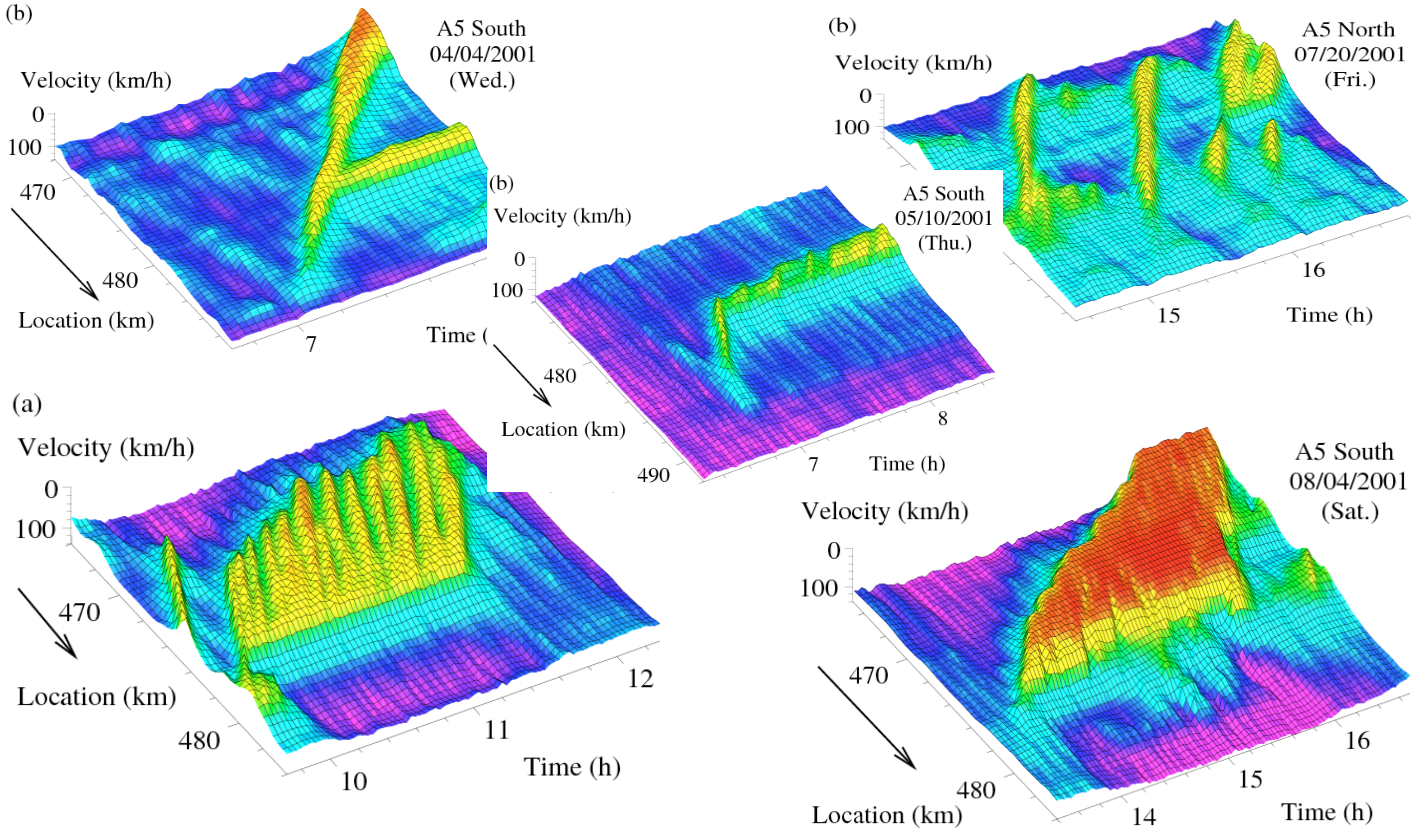


Elementary Traffic Patterns: Homogeneous Congested Traffic



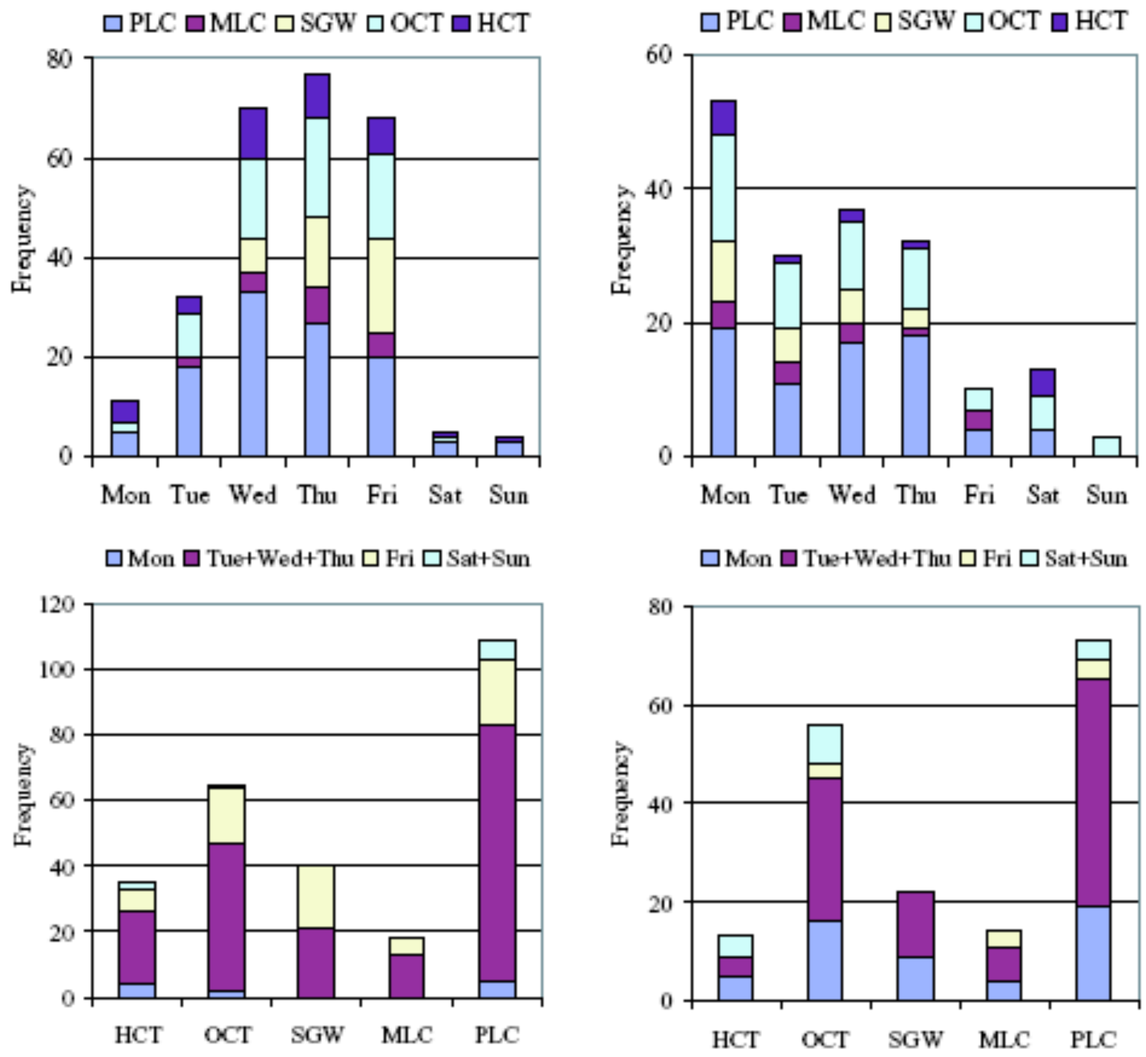
Homogeneous congested traffic requires large bottleneck strengths exceeding about 700 vehicles per kilometer and lane, which usually occur after serious accidents only. That is, if cases of accidents are excluded from the data set, one cannot find homogeneous congested traffic (if street capacities are properly dimensioned).

Summary of Elementary Congestion Patterns



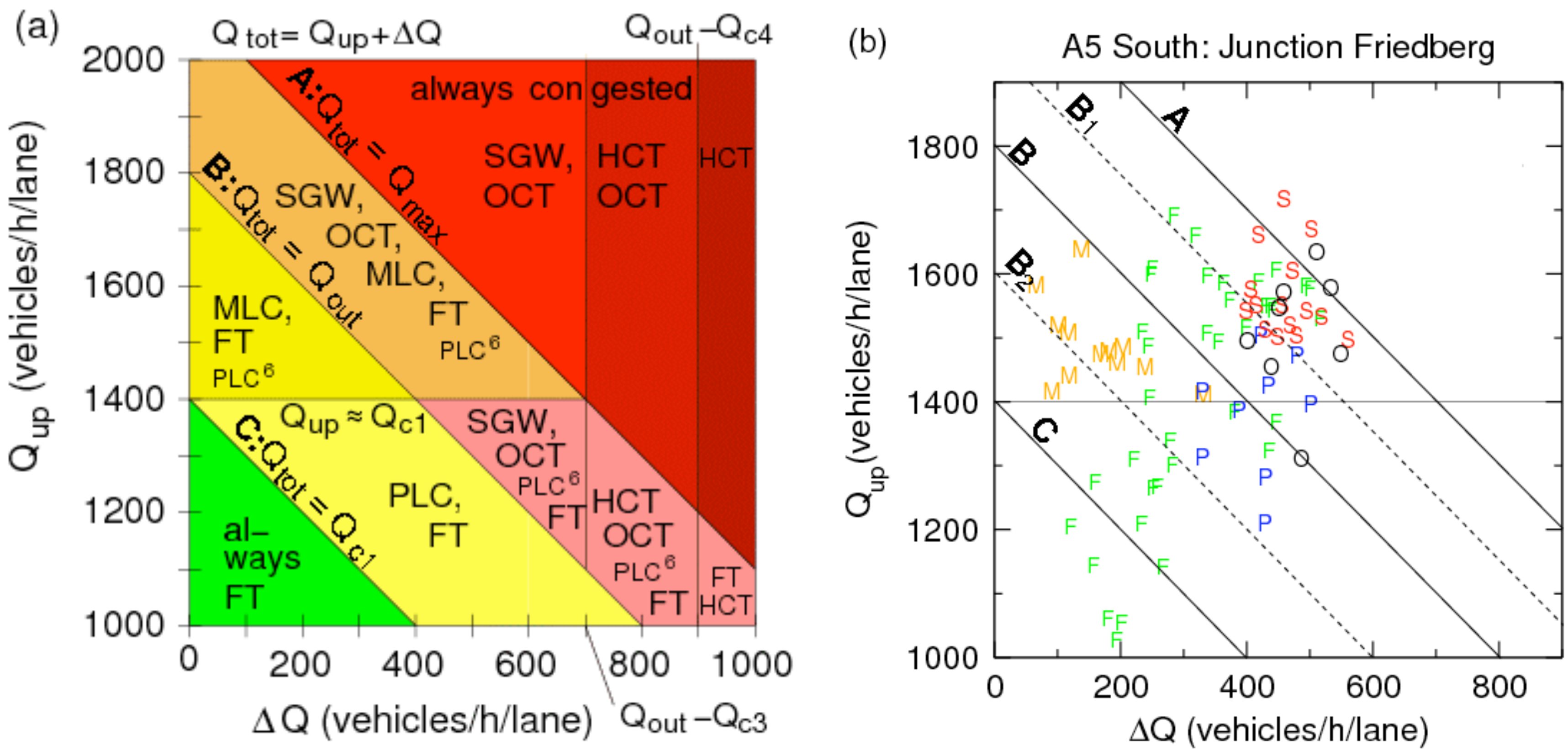
Traffic States Depend on the Weekday

Direction North of Frankfurt



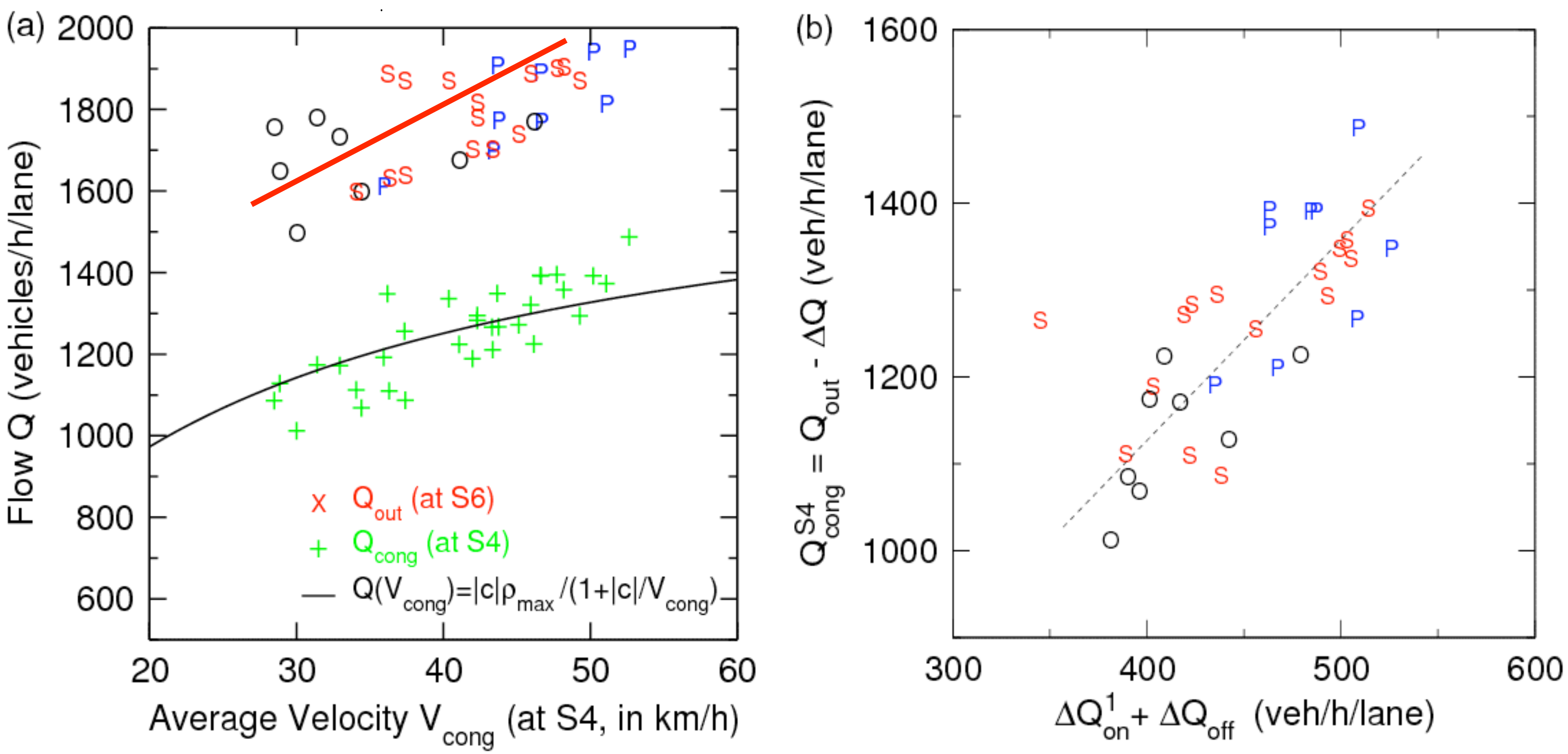
Direction towards Frankfurt

Theoretical vs. Empirical Phase Diagram



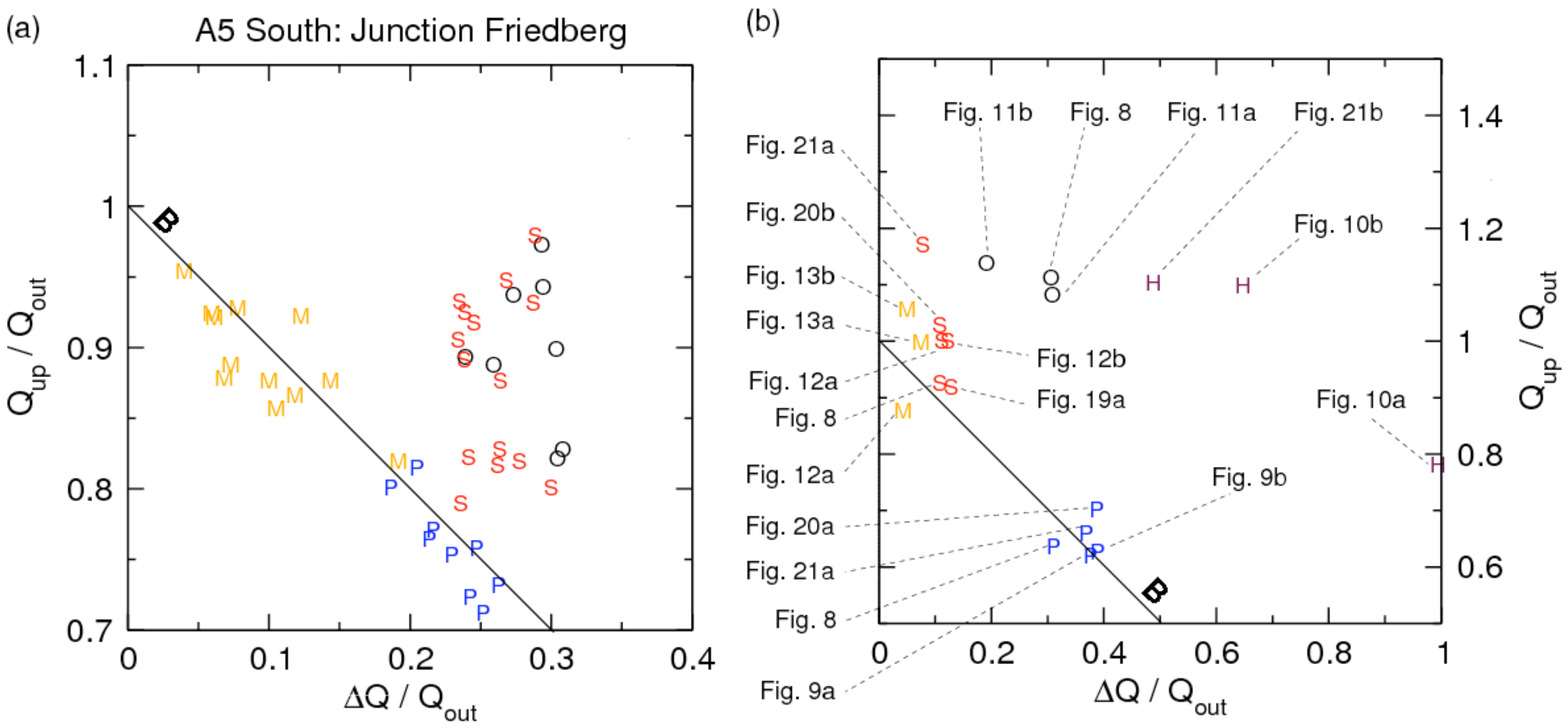
The outflow varies between B1 and B2. For statistical reasons?

The Outflow Correlates with Other Traffic Variables

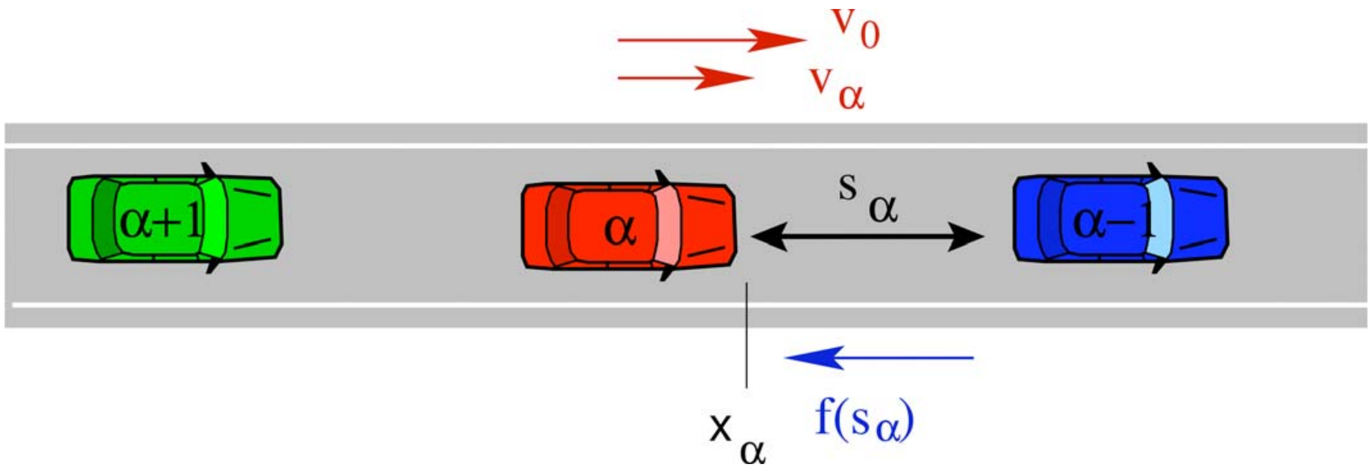


Empirical Phase Diagram for Scaled Flows

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



The Intelligent-Driver Model (IDM)



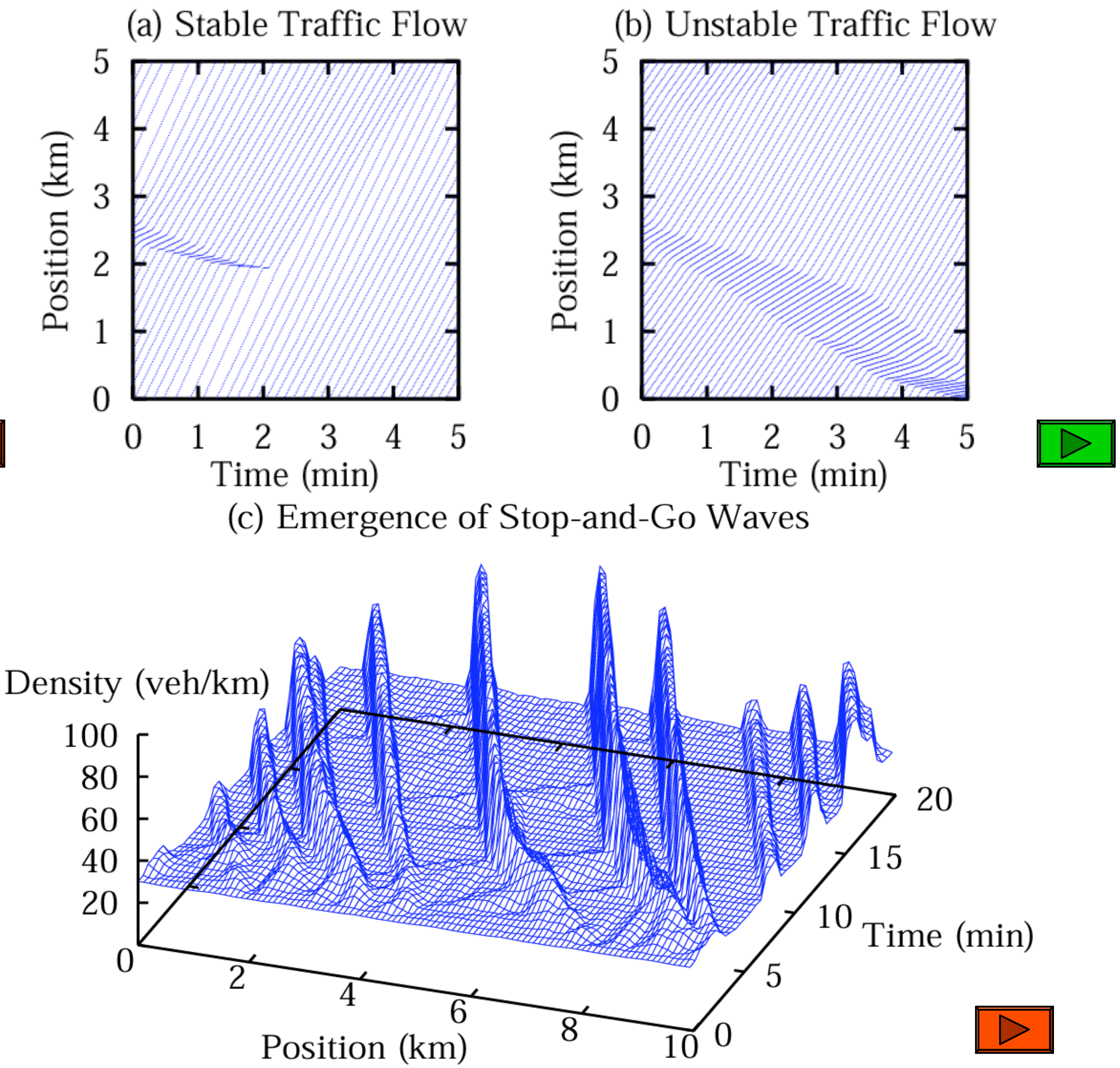
- Equations of motion:

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

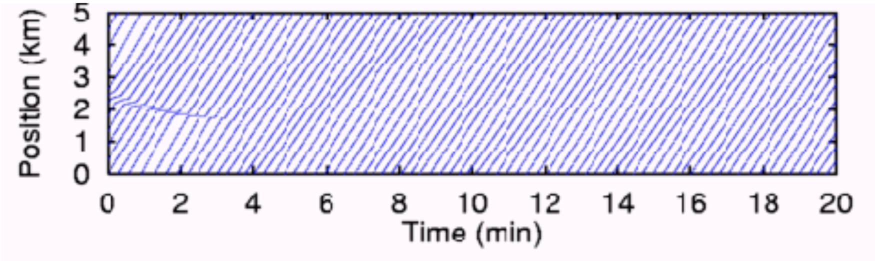
- Dynamic desired distance

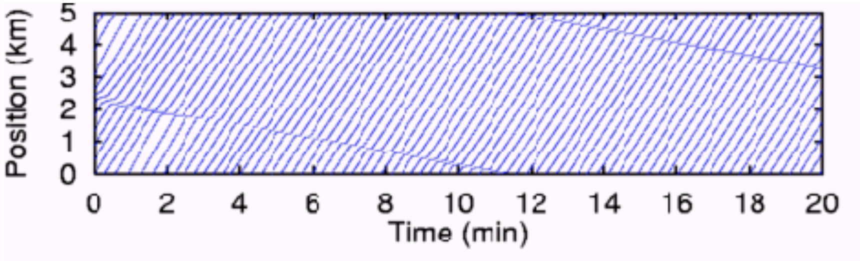
$$s^*(v, \Delta v) = \underbrace{s_0}_{\substack{\text{Mindest-}\\\text{abstand}}} + \underbrace{vT}_{\substack{\text{“Sicherheits”-}\\\text{abstand}}} + \underbrace{\frac{v\Delta v}{2\sqrt{ab}}}_{\substack{\text{dynamischer}\\\text{Teil}}}$$

Instability of Traffic Flow



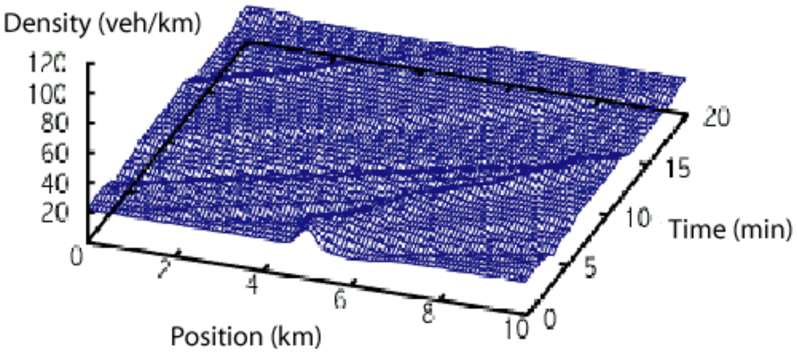
Metastability of Traffic Flow

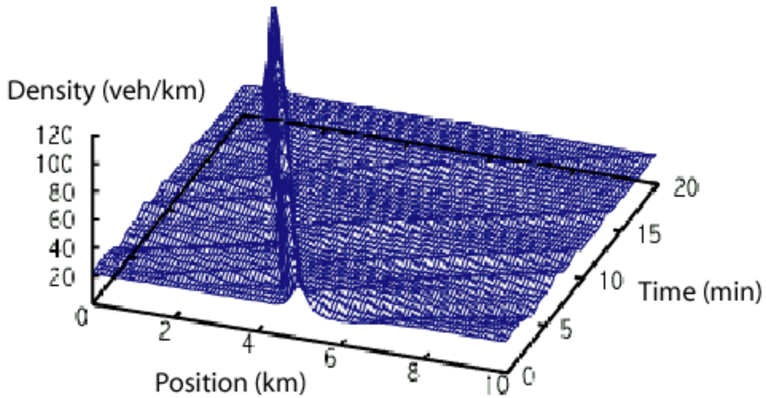




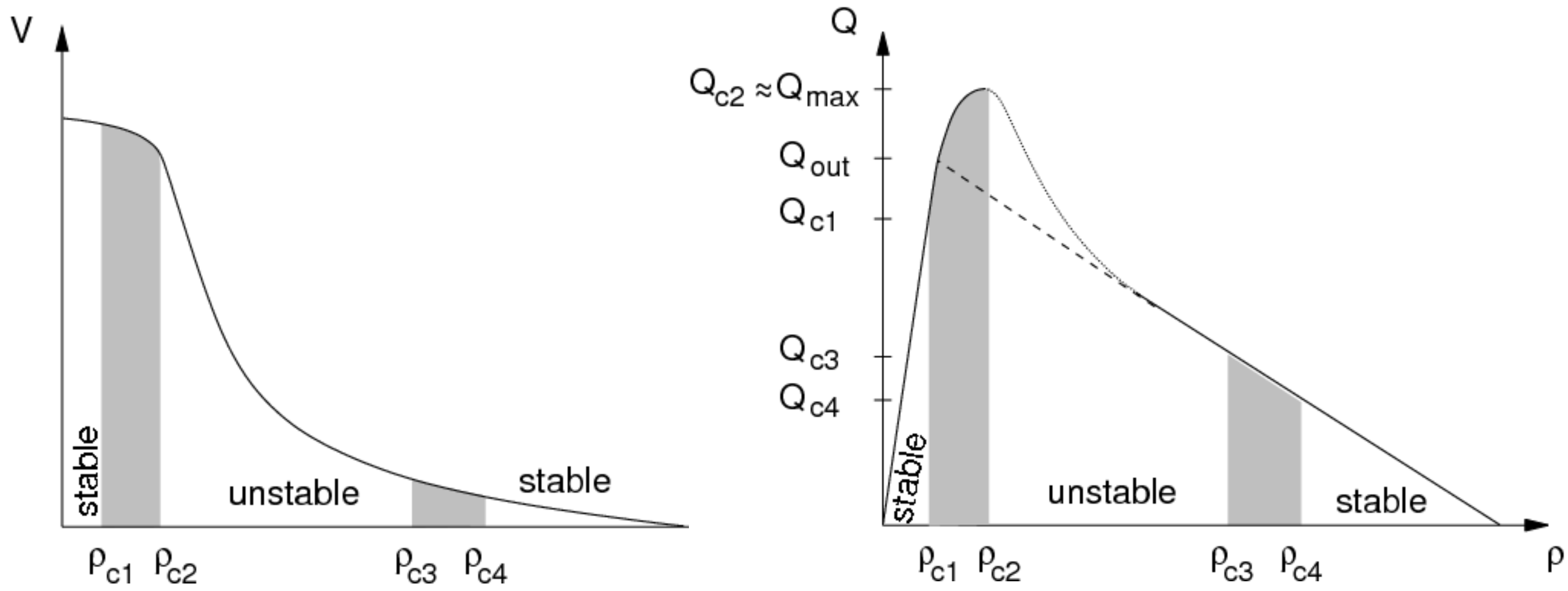
Decay of a Subcritical Perturbation

Growth of a Supercritical Perturbation





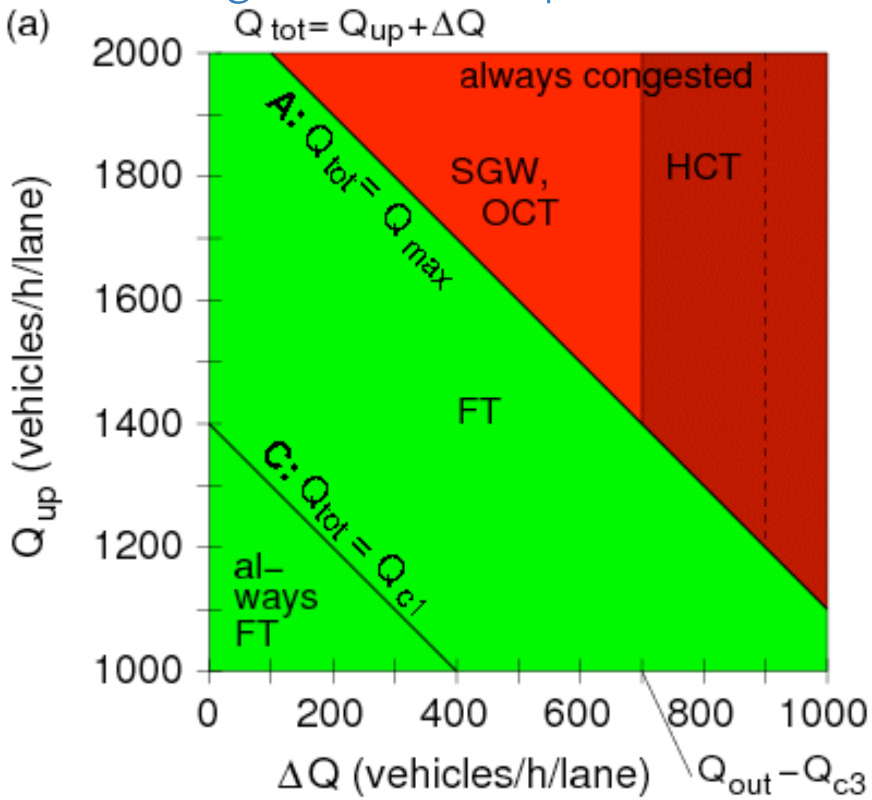
Assumed Instability Diagram



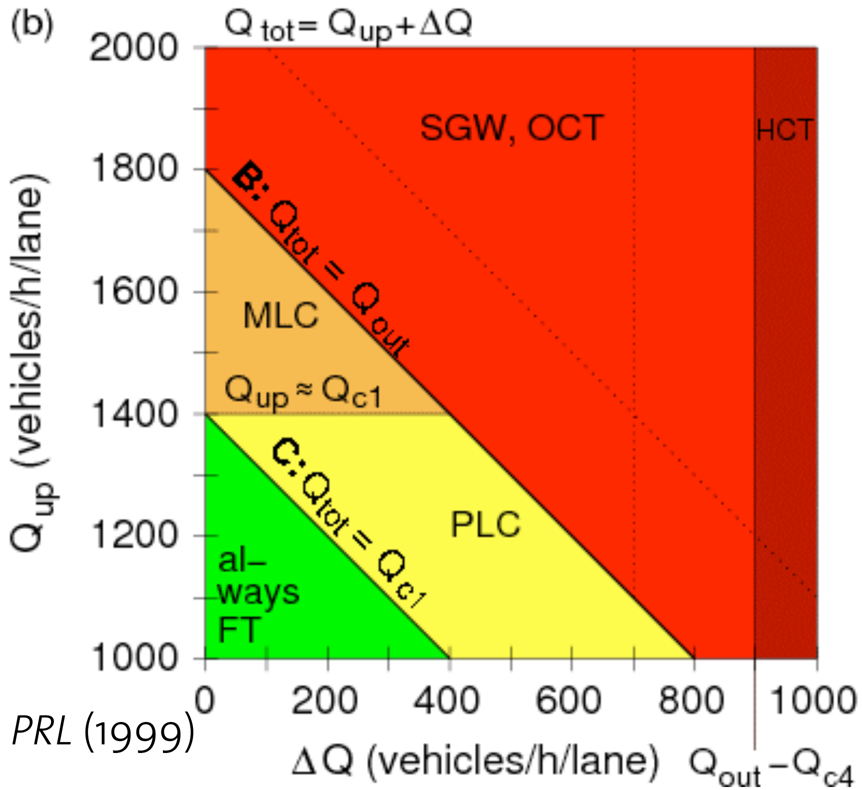
Grey areas = metastable regimes, where result depends on perturbation amplitude

Phase Diagram of Traffic States and Universality Classes

Phase diagram for small perturbations



for large perturbations

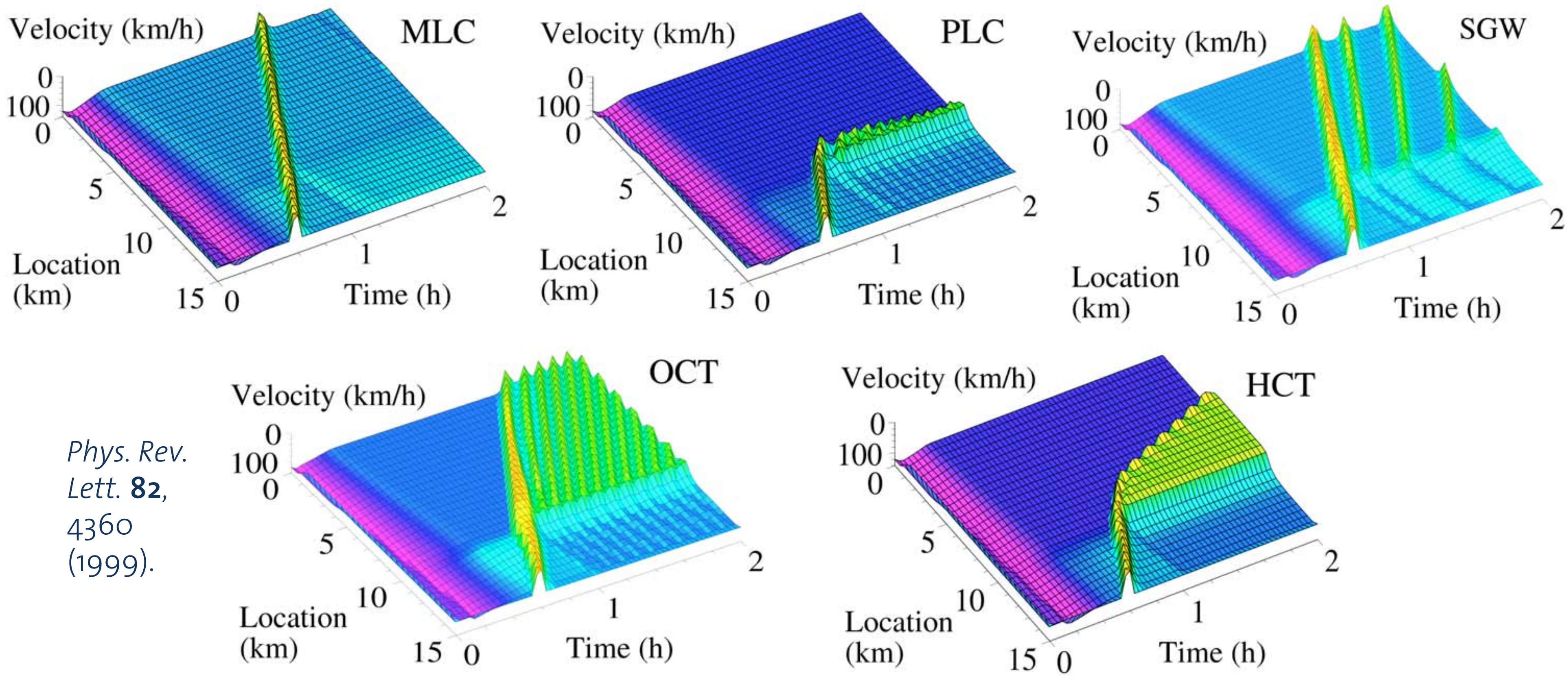


After: *PRL* (1999)

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.

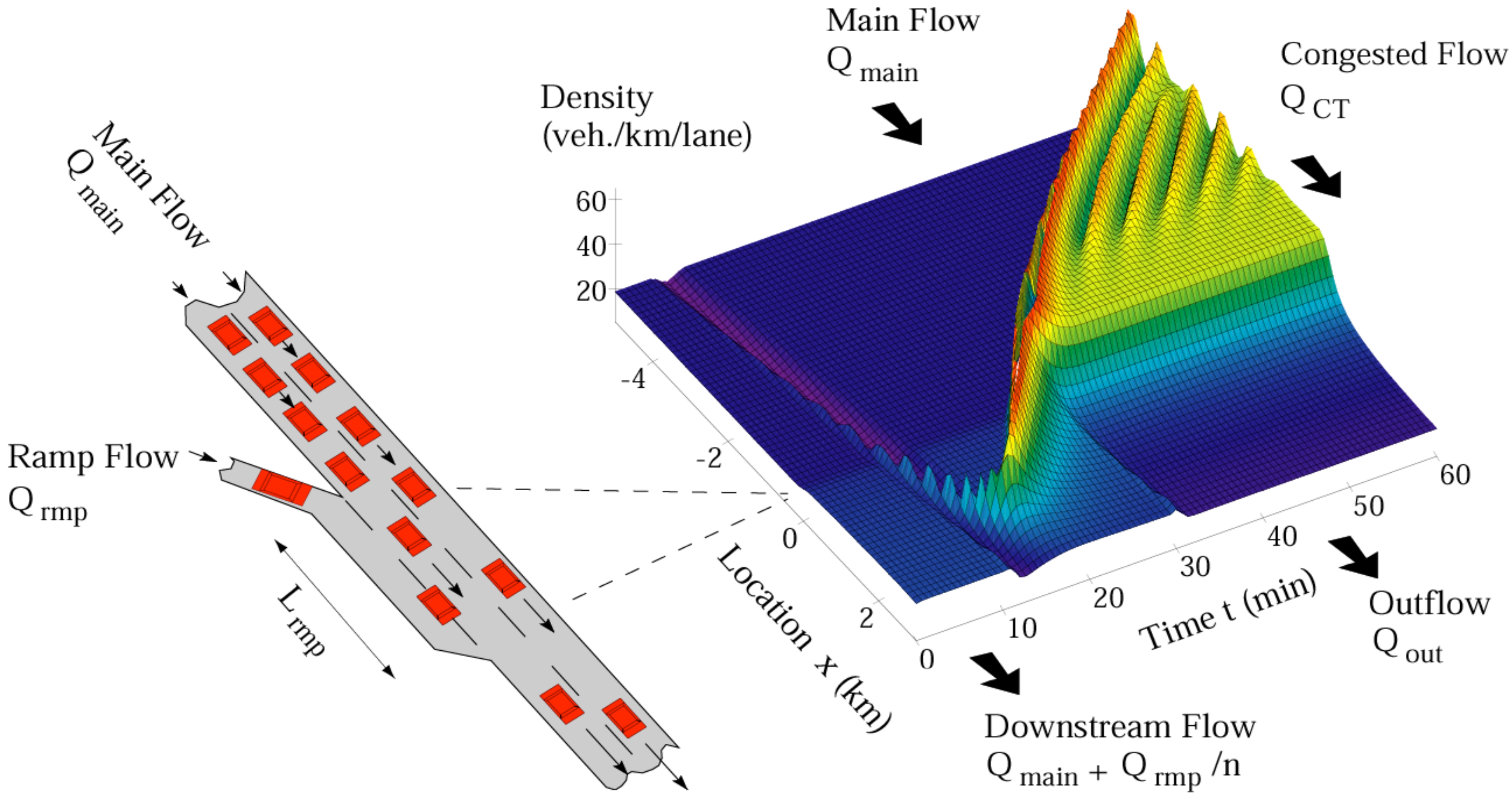


Phys. Rev. Lett. **82**, 4360 (1999).

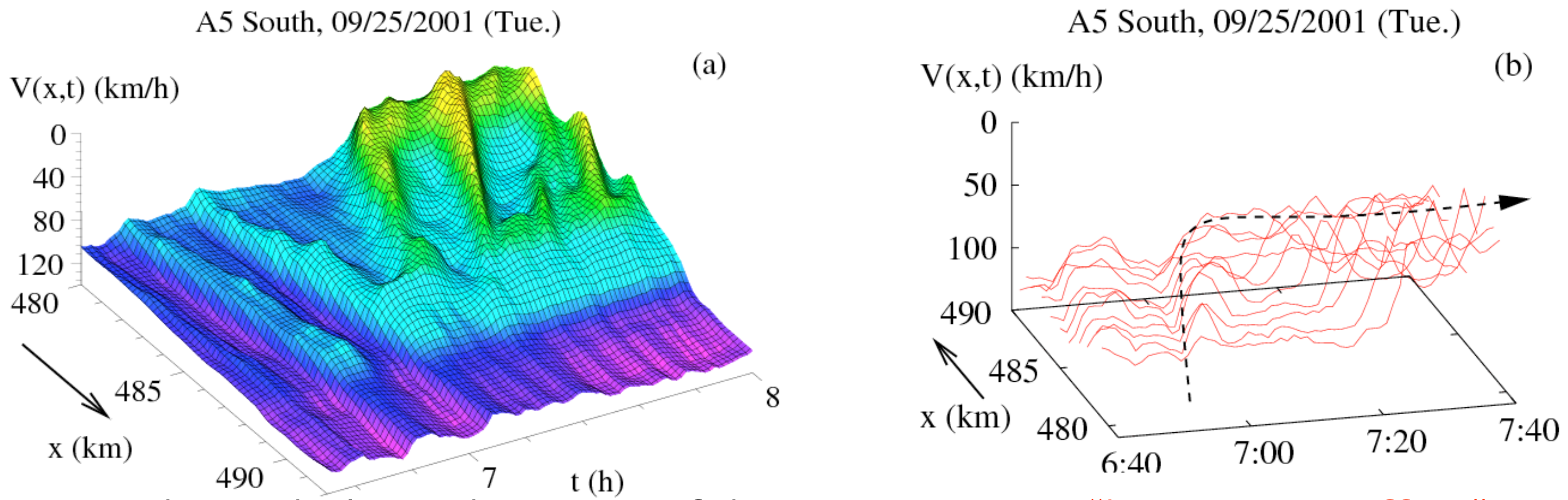
Similar congested traffic states are found for several other traffic models, including "microscopic" car-following models.

Breakdown of Traffic due to a Supercritical Reduction of Traffic Flow

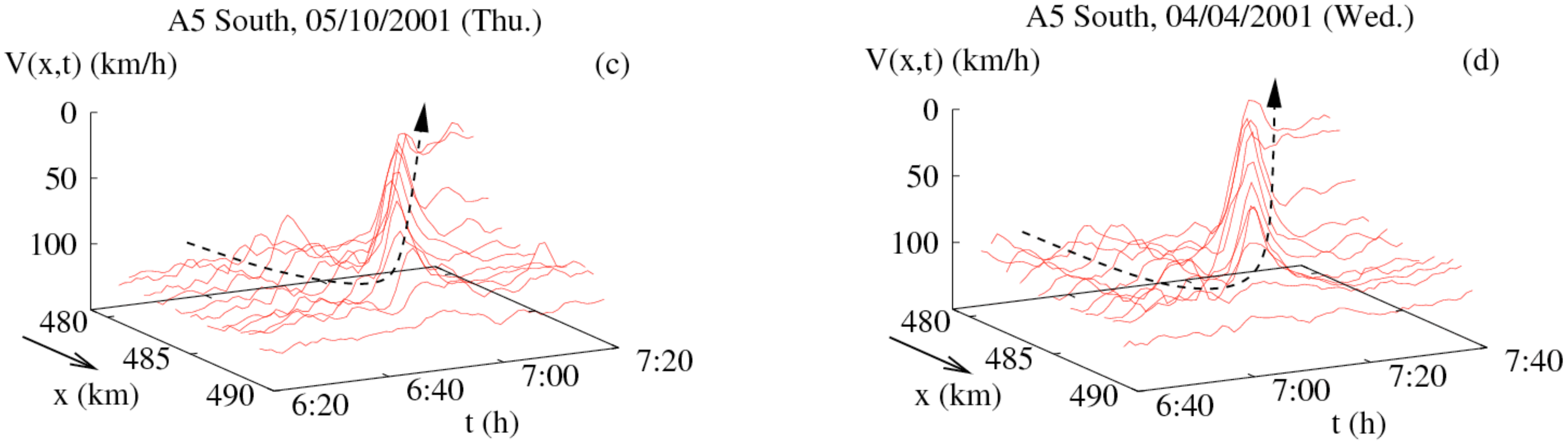
Negative Perturbation Triggering Oscillating Congested Traffic



Transitions from Free Traffic to Jams Do Exist

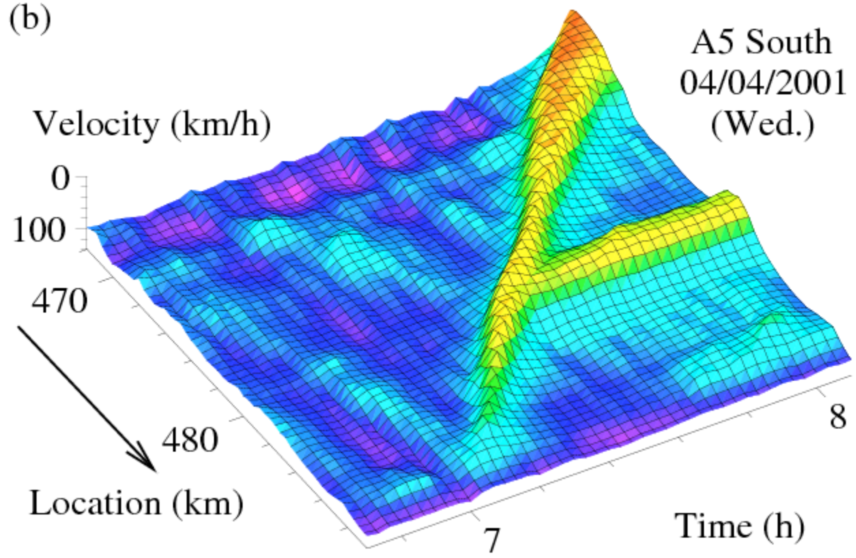


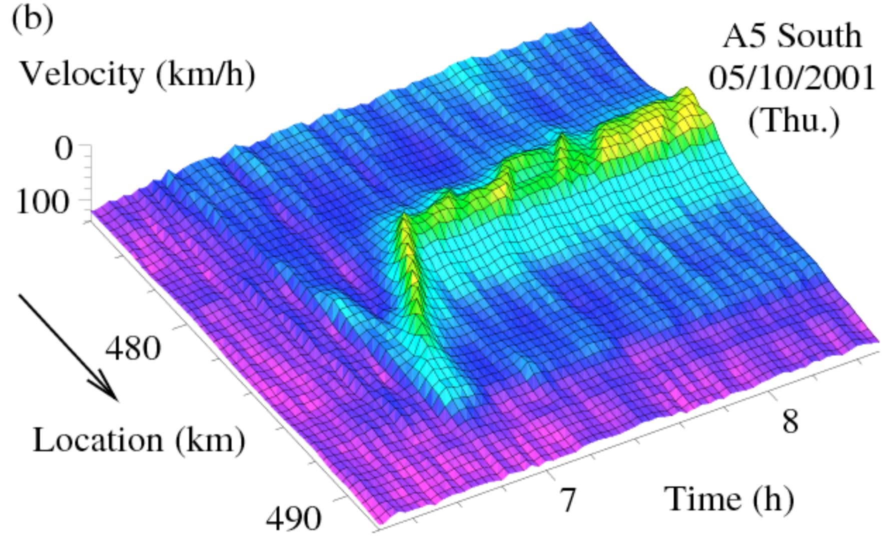
The underlying dynamics of this transition is a "boomerang effect"



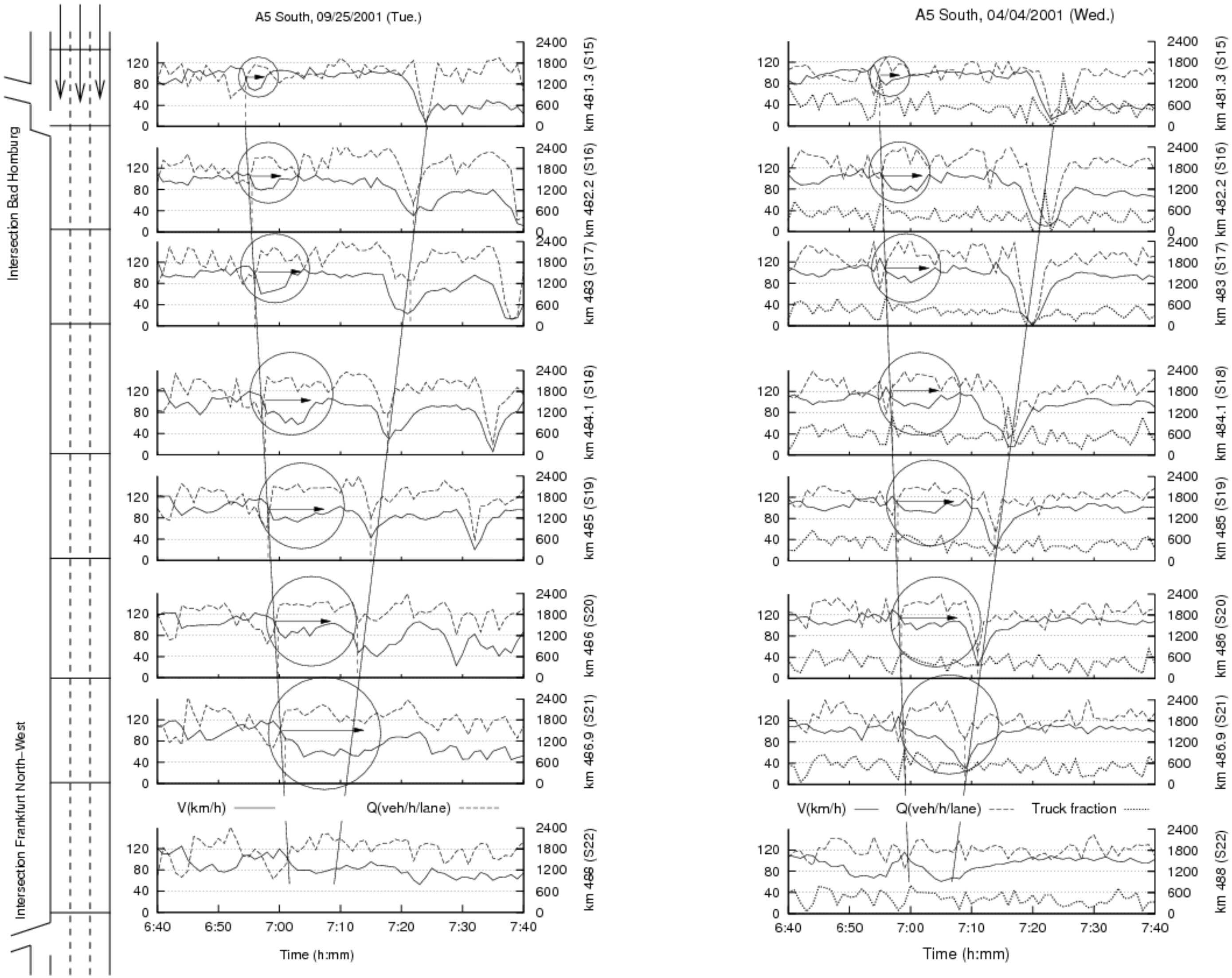
The boomerang effect was observed in 18 out of 245 cases of traffic breakdowns.

Examples of the “Boomerang Effect”

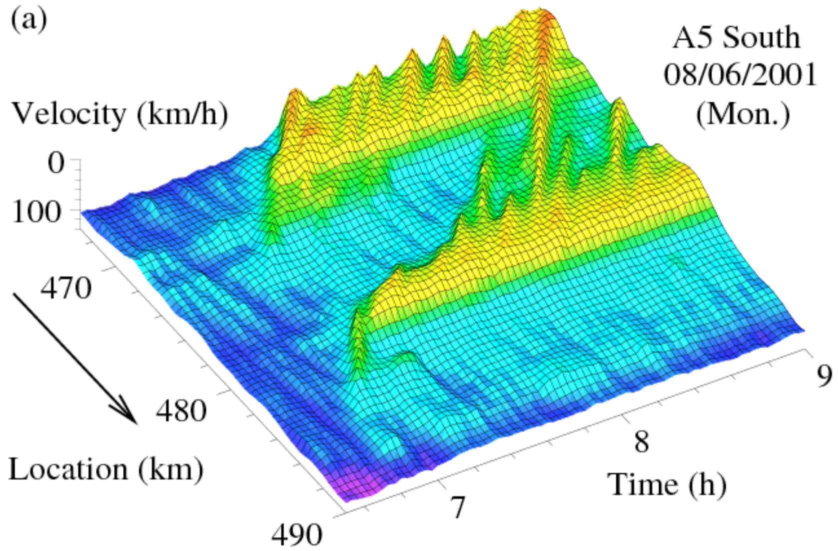


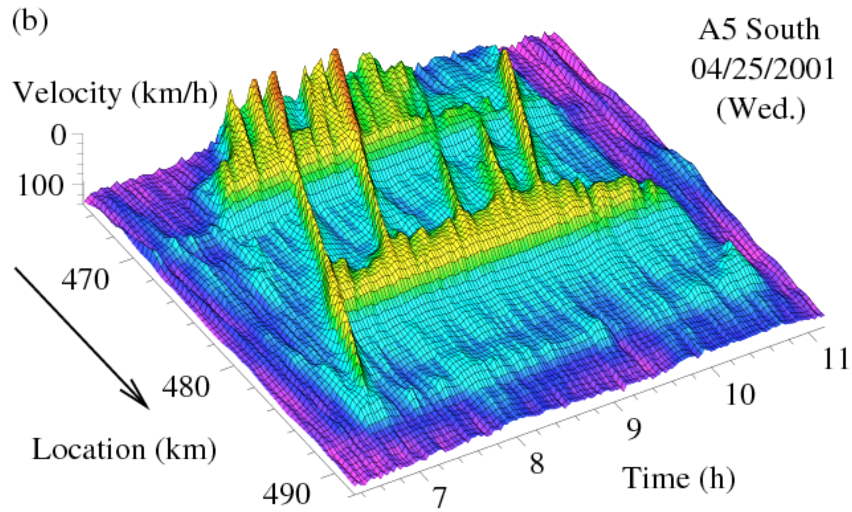


Boomerang Effects are Due to Overtaking Trucks



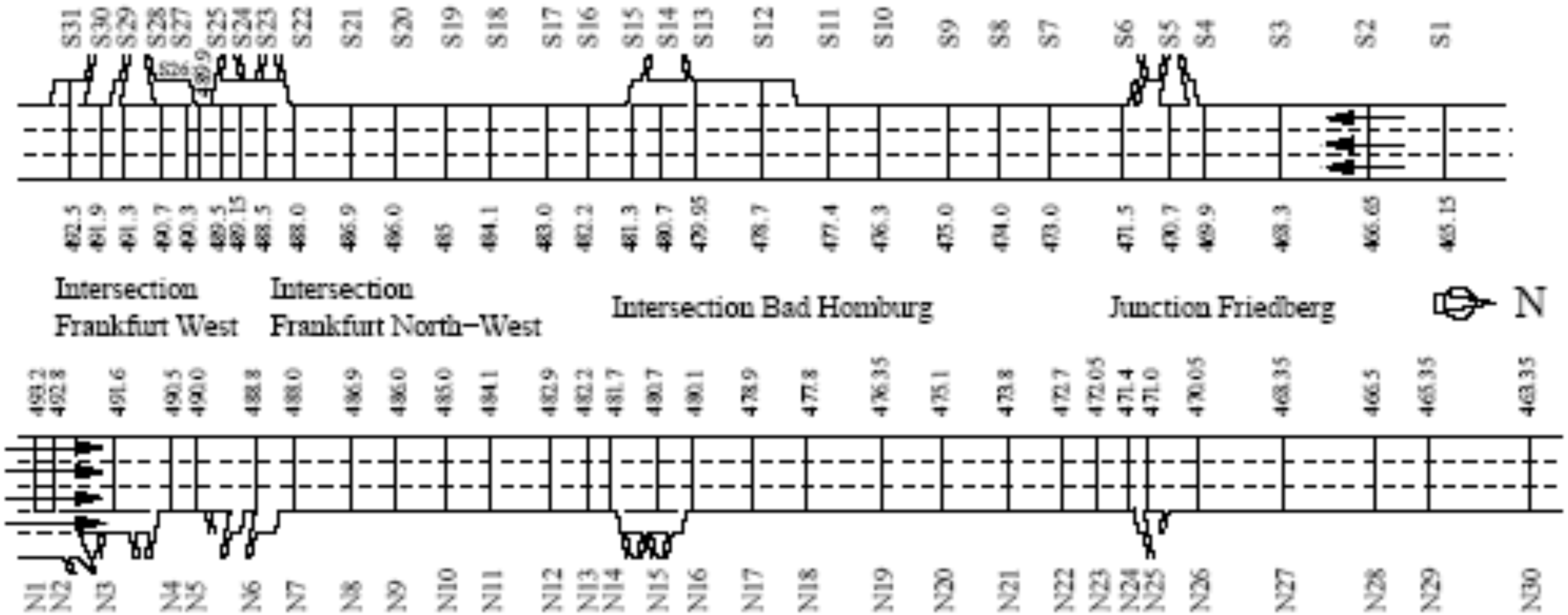
Discussion of the General Pattern and Pinch Effect





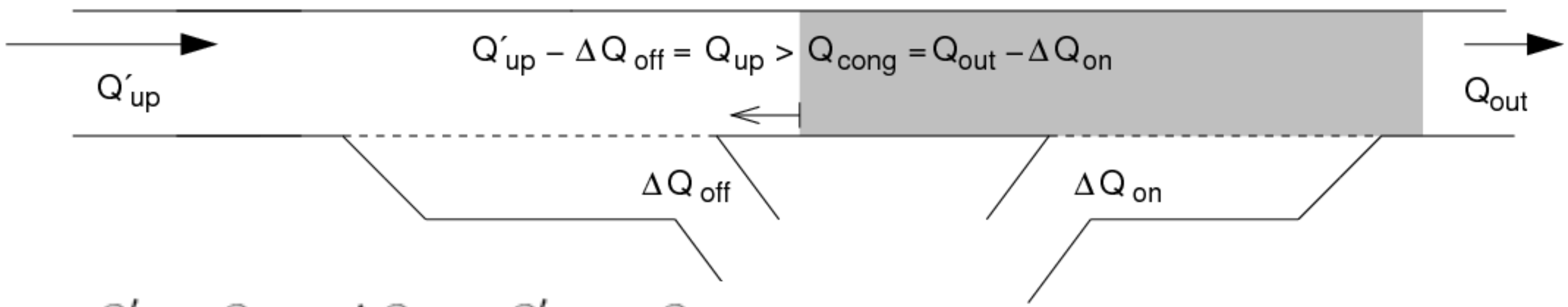
According to Kerner, in the "generalized pattern", synchronized traffic upstream of a bottleneck breads wide moving jams based on the "pinch effect". That is, upstream of a section with "synchronized" congested traffic close to a bottleneck, a so-called "pinch region" gives spontaneously birth to narrow 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.

Design of the German Freeway A5

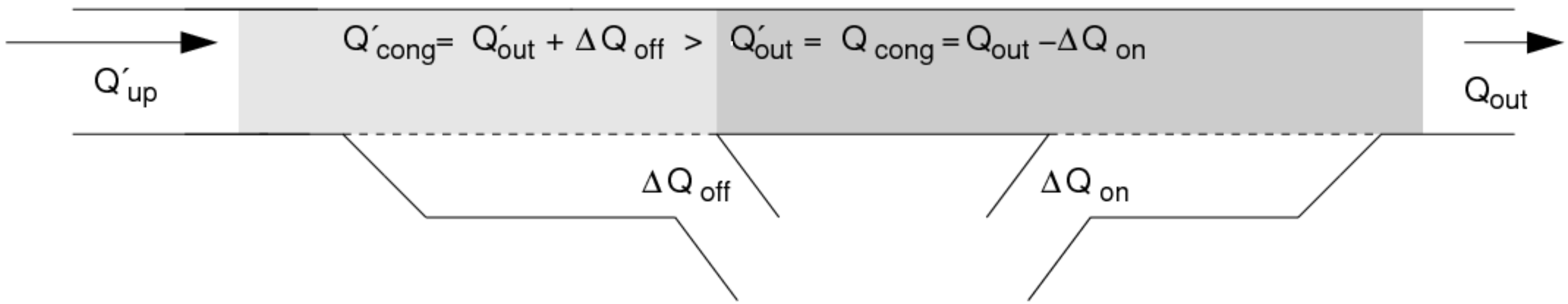


(Intermittent) Activation of an Off-Ramp Bottleneck

a)



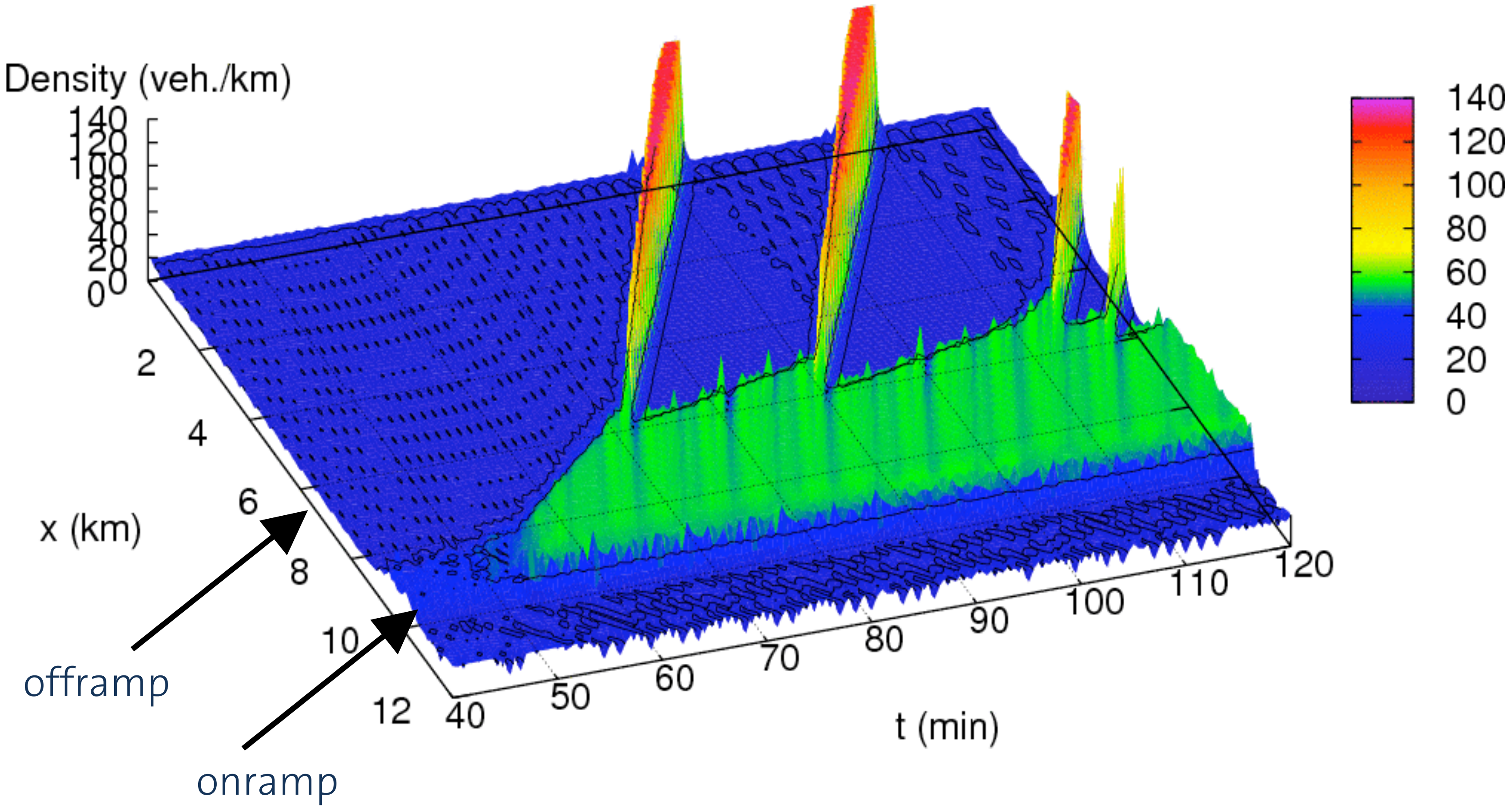
b) $Q'_{\text{up}} - Q_{\text{up}} = \Delta Q_{\text{off}} = Q'_{\text{cong}} - Q_{\text{cong}}$



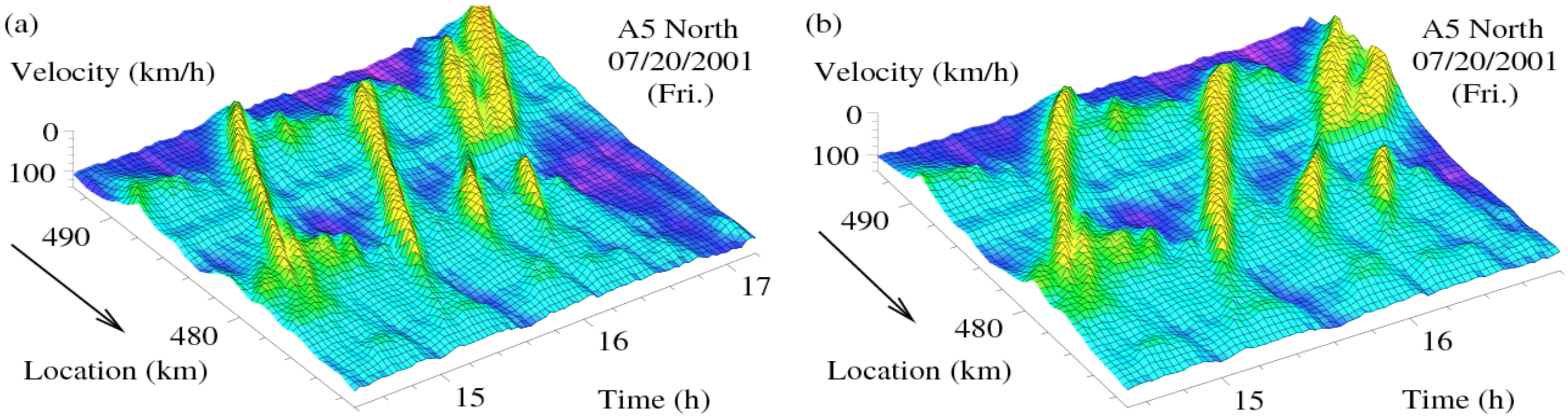
$$\Delta Q = \max(\Delta Q_{\text{on}} - \Delta Q_{\text{off}}, 0) = \max\left(\frac{Q_{\text{rmp}}}{n} - \frac{Q'_{\text{rmp}}}{n'}, 0\right) \le \Delta Q_{\text{on}}$$

Milder form of congested traffic upstream of off-ramp expected, e.g. OCT or SGW instead of HCT. Appearance would correspond to “generalized pattern”.

Combination of an Off-Ramp with an On-Ramp

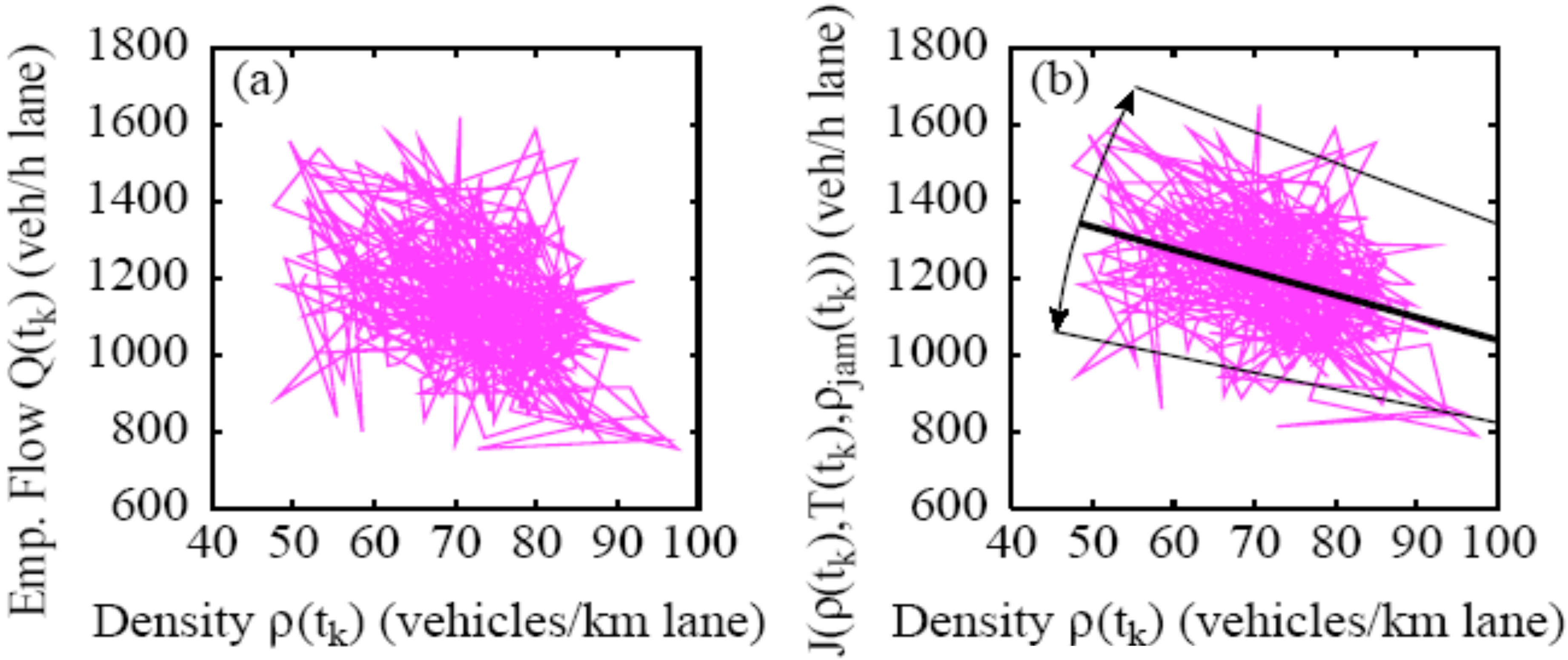


Stop-and-Go Waves Emerging at a Gradient Look Different



Instability of Traffic Flow

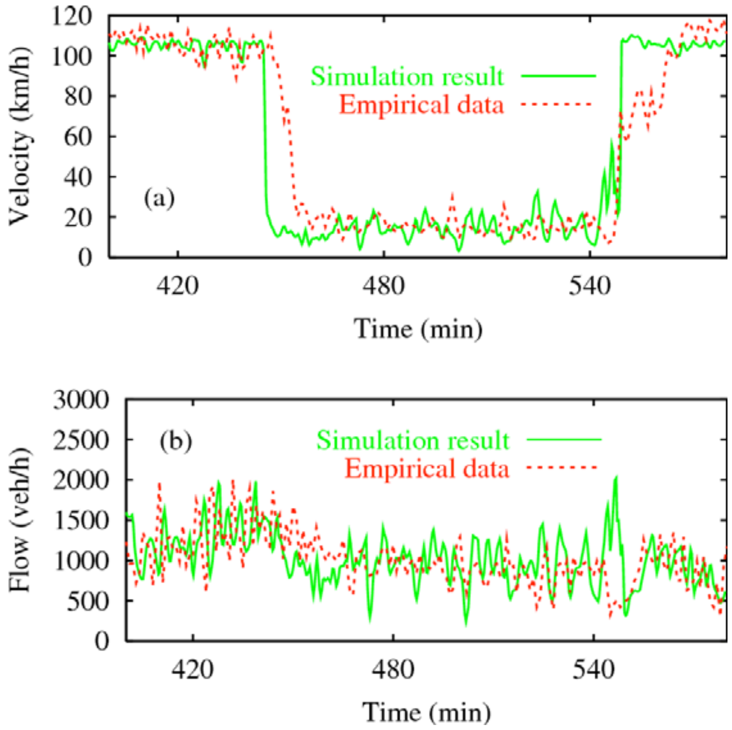
Wide Scattering as Effect of Heterogeneous Traffic



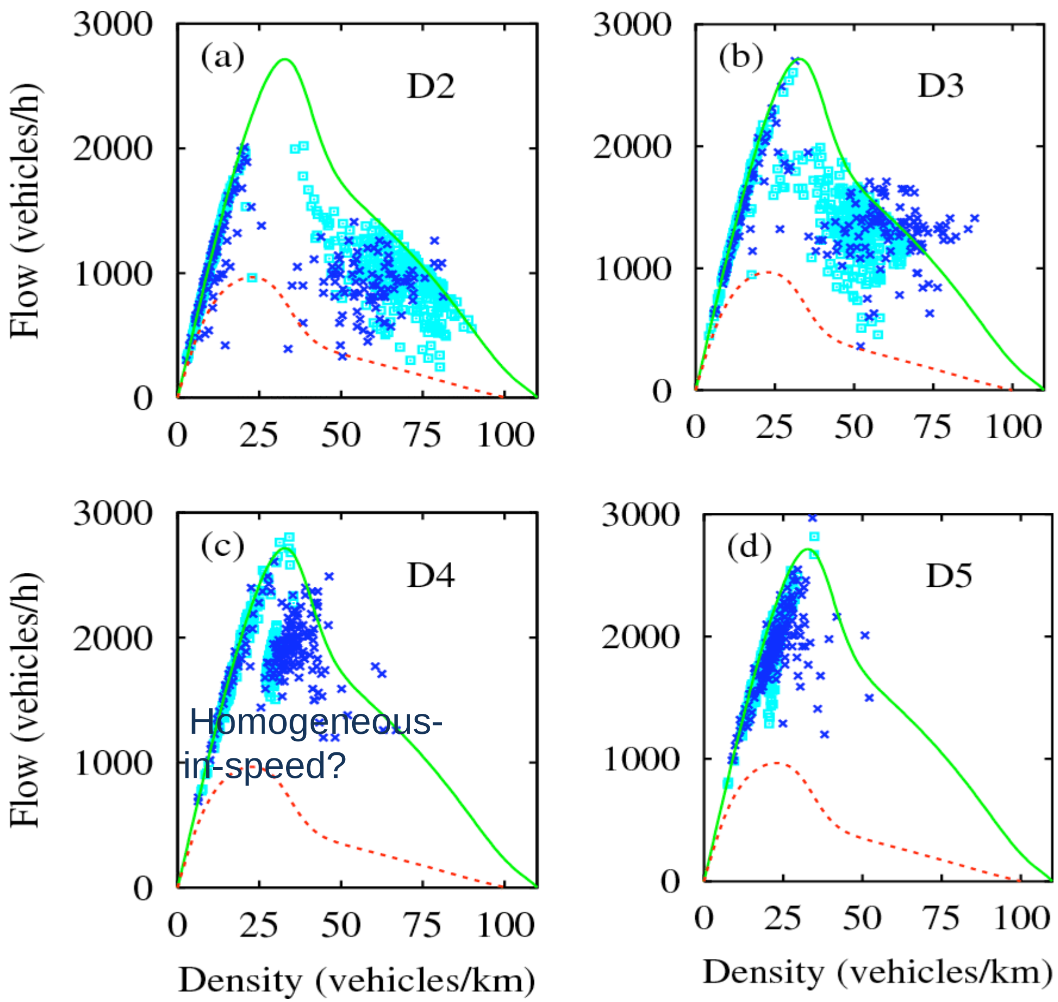
$$Q(t) = \frac{1}{T(t)}\left(1 - \frac{\rho(t)}{\rho_{\text{jam}}(t)}\right)$$

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.

Fluid-Dynamic Traffic Simulation of Multi-Class Traffic



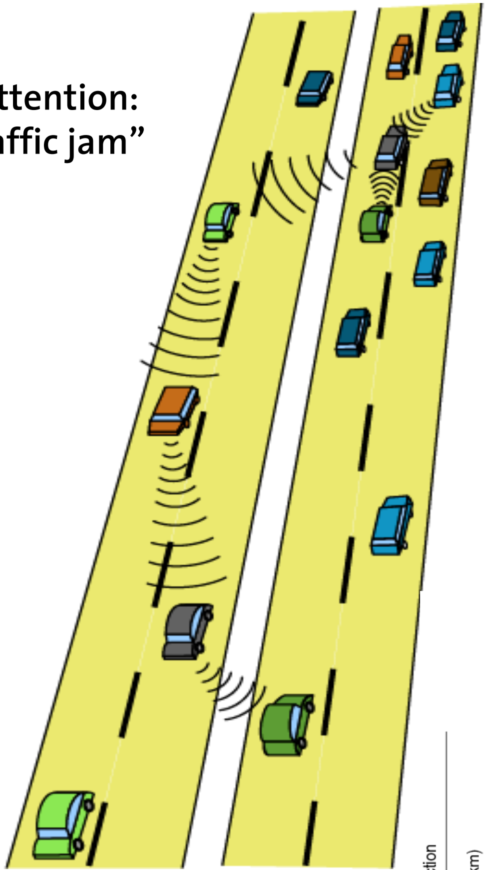
- Time series



- Fundamental diagram

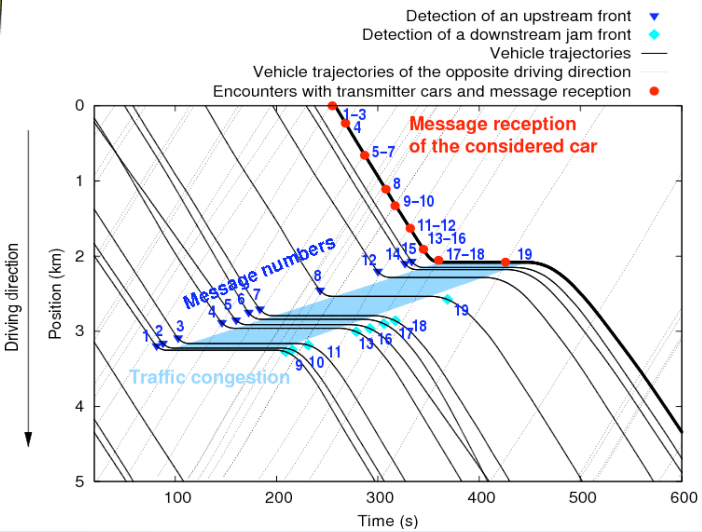
Cooperative Driving Based on Autonomous Vehicle Interactions

"Attention: Traffic jam"

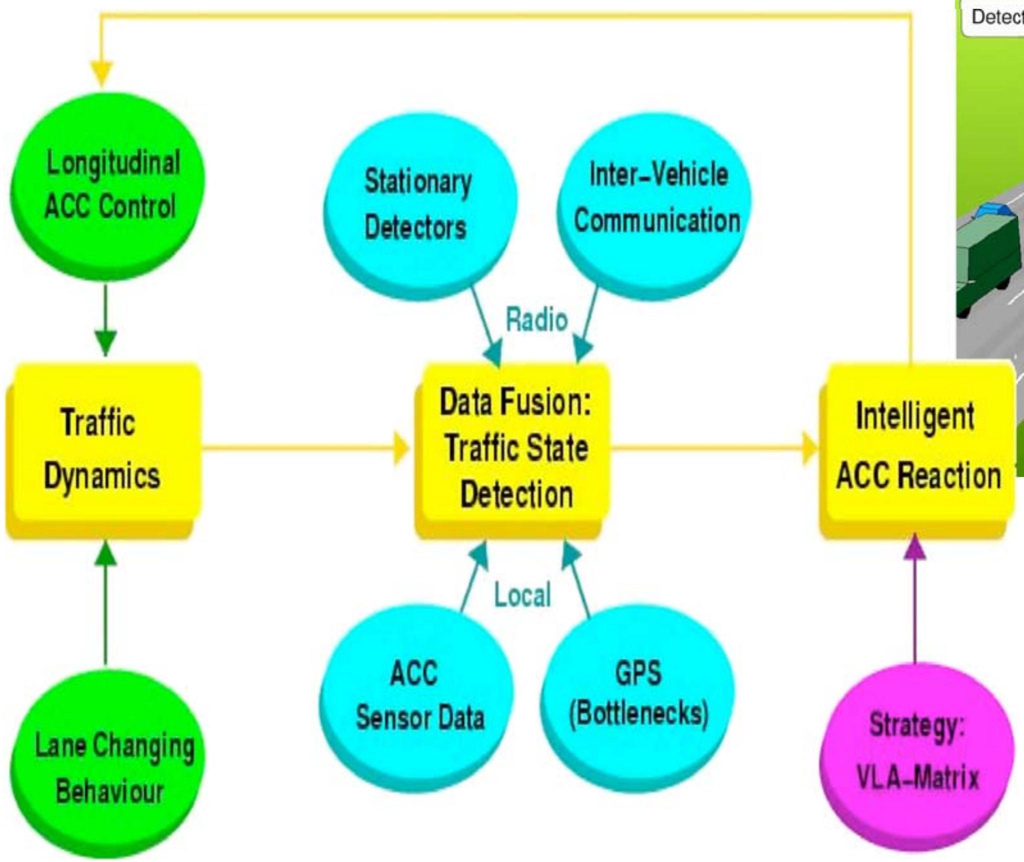


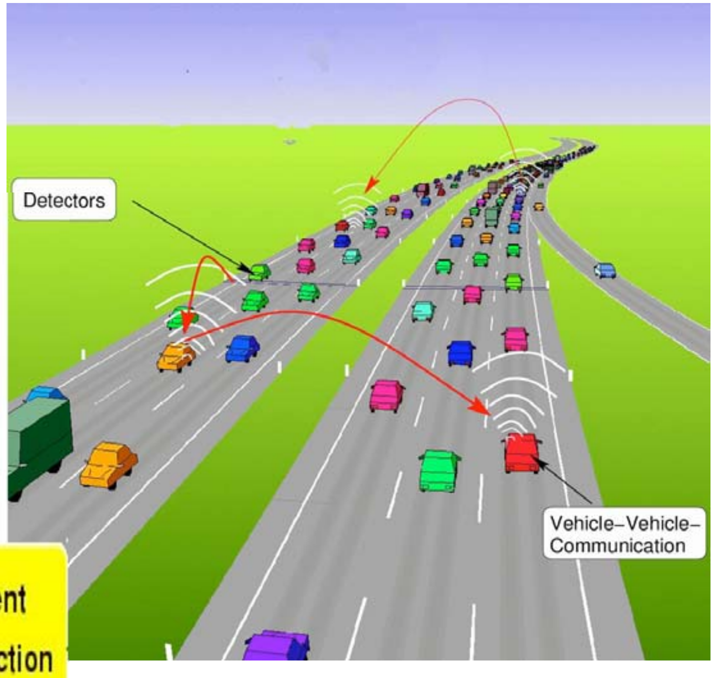
In: *Transportation Research Record* (2007)

- 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)



Data Fusion for Dynamic Traffic State Detection





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

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

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

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)

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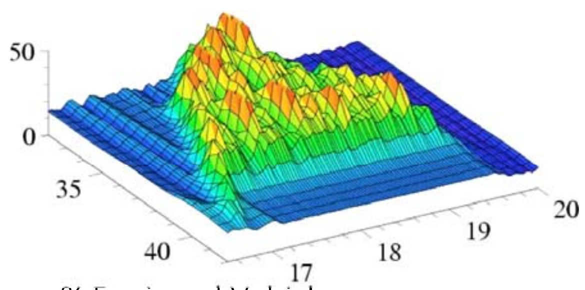
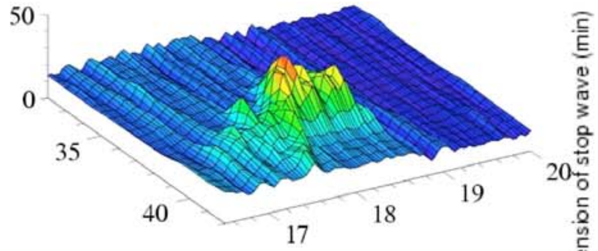
Swiss Federal Institute of Technology Zurich

Enhancing Traffic Performance by Adaptive Cruise Control

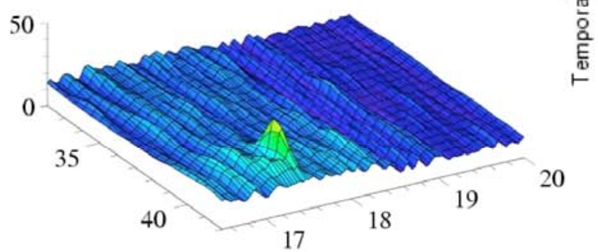
ρ(veh./km/lane)



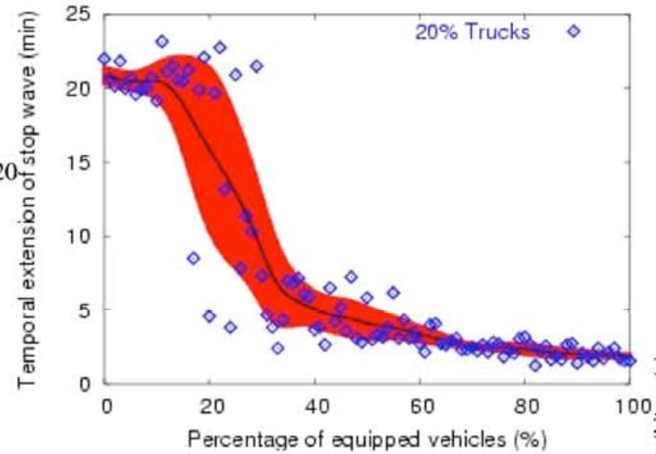
10% Equipped Vehicles

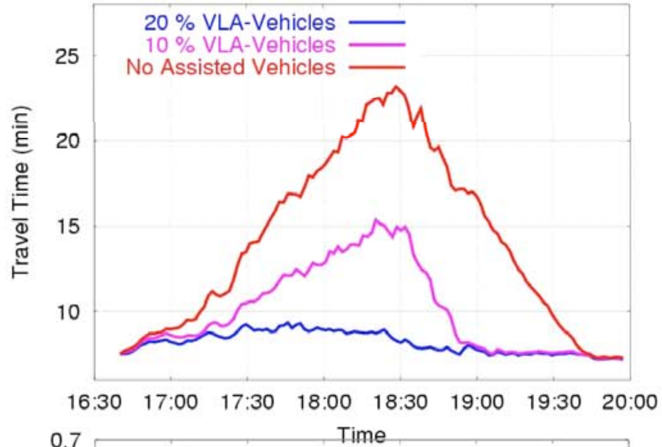


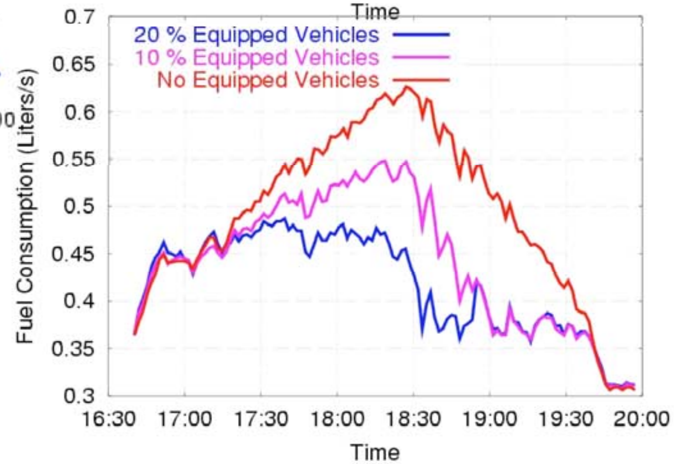
20% Equipped Vehicles



- 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