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

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with Stefan Lämmer, Reik Donner, Johannes Höfener, Jan Siegmeier, ...
Scaling Laws in the Spatial Structure of Urban Road Networks
Data Set and Publication

- Urban road network analysis of 20 largest cities of Germany (ranked by population)

- Geographical database: Tele Atlas MultiNet™

Acknowledgements

We thank Geoffrey West and Janusz Holyst for inspiring discussions, Winnie Pohl and Kristin Meier for their support of our data analysis, and for partial financial support within the DFG project He 2789/5-1. S. L. is grateful for a scholarship by the ‘Studienstiftung des Deutschen Volkes’.
Distinct Classes of Networks

- Random networks (Erdős and Rényi 1959)
  - Exponential node-degree distribution
  - High vulnerability to random failures

- Scale-free networks (Barabasi and Albert 1999)
  - Short distances (small world phenomenon)
  - High clustering coefficients
  - Power-law node-degree distribution

- Urban road networks (Gastner and Newman 2004)
  - Mainly planar cellular structure
  - Limited node-degrees (average strictly less than 6)
  - Very high network diameter, high redundancy

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

With a travel-distance-budget of \( r \) kilometers, a car driver can reach a neighborhood of size
\[
N(r) \sim r^2
\]

With a travel-time-budget of \( \tau \) minutes, a car driver can reach a neighborhood of size
\[
N(\tau) \sim \tau^d
\]

Dresden: \( d = 2.2 \)
Spatial Concentration of Traffic Flow

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

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

Typical values for $\beta$

<table>
<thead>
<tr>
<th>City</th>
<th>$\beta$</th>
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<tbody>
<tr>
<td>Berlin</td>
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<td>1.374</td>
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Concentration of Traffic on Road Meters

- Lorenz-Curve

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

Typical values for $g$

<table>
<thead>
<tr>
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<th>$g$</th>
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</table>
Cellular Structures

Distribution of cell-degrees (number of neighboring cells)

- Road networks
- Crack patterns
- Honey combs
- Dragon fly wings
Scaling of Cell Areas

Typical values for

<table>
<thead>
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<th>Cell Area</th>
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<td>Bonn</td>
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</table>

Cells with half the cell area are four times more frequent

\[ P(A/2) = 2^\alpha \approx 4 \]
Distribution of Form Factors

- Form factor $\varphi$: Fraction of the circumscribed circle that is covered by the cell
  - $\varphi=0 \ldots$ long and narrow
  - $\varphi=1 \ldots$ compact and round

- High values of $\text{Var}(\varphi)$ imply
  - Irregular network structure, e.g. city has grown over many epochs
  - Difficult to navigate from car driver’s point of view

<table>
<thead>
<tr>
<th>City</th>
<th>$\text{Var}(\varphi)$</th>
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<tbody>
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Intermediate Conclusions

- Scaling of neighborhood sizes
  - Fast roads let neighborhoods grow fast
  - Effective dimension of urban space is significantly higher than two (although mainly planar)

- Scaling of traffic flow
  - Estimation of traffic based on betweenness centrality
  - Power-law distribution of traffic flow on nodes
  - We found quantitative measures to characterize concentration of traffic

- Scaling of cell areas
  - Power-law distribution of cell areas
  - We found quantitative measures to characterize irregularity of cellular structure
Implementation of an Decentralized and Self-Organized Traffic Light Control
Optimal Traffic Flow Control and Production Scheduling

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

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

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

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

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

Road Networks

Directed Links:
- Road sections
- Travel- and delay time
- Congestion, queues

Nodes:
- Junctions
- Different origin-destination
- Conflicting flows
- Traffic light scheduling
- Green Wave
- Accidents

Production Networks

Directed Links:
- Buffers
- Cycle time
- Full buffers

Nodes:
- Processing units
- Different products flows
- Conflicts in usage of gripper, transfer cars etc.
- Production scheduling
- ConWiP strategy
- Machine breakdowns
Adaptive Traffic Light Control

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

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

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

*Local Rules, Decentralization, Self organization*
Traffic Dynamics: Macroscopic Approach

- “Traffic is a fluid medium.”
  - Describing values:
    - $V$ ... velocity (in m/s)
    - $\rho$ ... density (in vcl/m)
    - $Q$ ... flow (in vcl/s)

- 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 $\rho$ are empirically correlated.”

\[ Q_e(\rho) \]

Derivation $Q_e'$ plays important role!

\[ \frac{\partial \rho}{\partial t} + \frac{dQ_e(\rho)}{d\rho} \cdot \frac{\partial \rho}{\partial x} = 0 \]
Traffic Dynamics: Shock Waves

- Propagation velocity $c(\rho)$
  \[ c(\rho) = \frac{dQ_e(\rho)}{d\rho} \]

- Free traffic:
  - $c(\rho) = V^0$

- Congested traffic:
  - $c(\rho) \approx -15 \text{ km/h (universal)}$
Characteristic Velocities

Roadway $x$

$0$

$\frac{1}{\rho_{\text{jam}}}$

$t_0$

$t_0 + T$

Time $t$

$1/Q_i^{\text{max}}$

$V^0$

$c$
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

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

$V_i^0 = \text{free speed on road section } i$

$T = \text{safe time gap}$

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

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

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

$Q_{i+1} = \text{arrival rate of vehicles}$

$Q_{i-1} = \text{departure rate of vehicles}$

Treatment of ramp flows at downstream section ends:

$$Q_{i+1}(t) = Q_i(t) + Q_{\text{ramp}}(t)$$
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:

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

\[l_i = \text{number of lanes}\]

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

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:

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

\[L_i = \text{length of road section } i, \quad l_i = \text{length of congested road section}\]
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
  \[
  \frac{d}{dt} x_i^{FC} = \frac{\Delta Q(x_i^{FC})}{\Delta \rho(x_i^{FC})}
  \]

- Number of vehicles
  \[
  \frac{d}{dt} N_i(t) = Q_i^{arr}(t) - Q_i^{dep}(t)
  \]

- Travel time
  \[
  \frac{d}{dt} T_i(t) = 1 - \frac{Q_i^{dep}(t)}{Q_i^{arr}(t - T_i(t))}
  \]
Network Nodes: Connectors

- **Side Conditions**
  \[ \sum_i Q_i^{\text{dep}} = \sum_j Q_j^{\text{arr}} \]

- **Conservation**
  \[ Q_i^{\text{dep}} \geq 0 \]
  \[ Q_j^{\text{arr}} \geq 0 \]

- **Non-negativity**
  \[ Q_i^{\text{dep}} \leq Q_i^{\text{dep, pot}} \]
  \[ Q_j^{\text{arr}} \leq Q_j^{\text{arr, pot}} \]

- **Upper boundary**
  \[ \sum_i \alpha_{ij} Q_i^{\text{dep}} = Q_j^{\text{arr}} \]

- **Branching**
  \[ F = \sum_i f(Q_i^{\text{dep}}) \rightarrow \text{max} \]

- **Goal function**
  \[ f(x) = x^p \text{ with } p \ll 1 \]
Network Nodes: Special Cases

- **1 to 1:**
  \[ Q_{i}^{\text{dep}} = Q_{j}^{\text{arr}} = \min \left\{ Q_{i}^{\text{dep, pot}}, Q_{j}^{\text{arr, pot}} \right\} \]

- **1 to n:** Diverging
  \[ Q_{i}^{\text{dep}} = \min \left\{ Q_{i}^{\text{dep, pot}}, \min_{j} \frac{Q_{j}^{\text{arr, pot}}}{\alpha_{ij}} \right\} \]
  \[ Q_{j}^{\text{arr}} = \alpha_{ij} Q_{i}^{\text{dep}} \]

- **n to 1:** Merging
Simulation of Diverges and Merges
Attractiveness of Sinks

Mathematically, sinks tend to attract their vehicles similar to electric charges in a wire.
Network Representation of Intersections
Variability of Urban Traffic Flows

![Graphs showing variability of urban traffic flows.](image)

- **T=0.5h**, **T=1h**, **T=2h**, **T=3h**

- **S=8 ± 0.1**, **S=10 ± 0.1**, **S=12 ± 0.1**

- **Density=35 vehicles/km**

- **Density=40 vehicles/km**

- **Density=50 vehicles/km**

- **Number of Full Links (Units of road sections)**

- **Standard Deviation of Number of Vehicles**

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Intersections: Modelling

- Traffic light
  - Additional side condition

  \[ Q_{i,\text{dep}}(t) \leq g(t) \cdot Q_{i,\text{max}} \]

- 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

- Green wave
- Non-optimal phase shift
- 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
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
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
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

Optimal compromise between coordination and local flexibility

Published in *JSTAT* (2008)
Properties of the Self-Organized Traffic Light Control

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

A fully adaptive traffic light operation means:

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

![Diagram showing distance from stop line and time with variable prognosis horizon](image)
Local Optimization by Assigning Priorities

What queue to serve first?  When to interrupt a service process?  What time gaps are acceptable?

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

$$\sigma = \arg \max_i \{ \pi_i \mid \pi_i > 0 \}$$

An optimizing traffic light control results, when serving the road with highest priority.
Behavior of the Optimizing Controller in Time

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

Flexible scheduling for random arrivals:

Because of the limited optimization horizon, instabilities can not be excluded!
Network-Wide Stability

Improved control strategy:

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

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

This leads to minimum switching delays

(stab.avi)

Linear convergence to a limit cycle
Combination of an Optimizing and a Stabilizing Controller

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

\[ \lambda_{\text{nord}} = 0.1 \]
\[ q_{\text{nord}} = 180 \text{ Fz/h} \]

\[ \lambda_{\text{ost}} = 0 \ldots 0.4 \]
\[ q_{\text{ost}} = 0 \ldots 1440 \text{ Fz/h} \]

\[ \lambda_{\text{west}} = 0 \ldots 0.4 \]
\[ q_{\text{west}} = 0 \ldots 1440 \text{ Fz/h} \]

\[ \lambda_{\text{sid}} = 0.1 \]
\[ q_{\text{sid}} = 180 \text{ Fz/h} \]

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)

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

Irregular switching patterns are equalizing irregular traffic patterns, and thereby minimizing waiting times.
Coordination in a Network

Traffic demand is specified with empirical data:

Simulated network:
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

Tram 1

Tram 2

Tram 6

Tram 10

Tram 11

Bus 75

Bus 94

CarGoTram
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

- Public transport
  - State-of-the-Art Control
  - Flexible Self-Control

- Motorized traffic
  - State-of-the-Art Control
  - Flexible Self-Control

Traffic volume (% of measured flow)
Red Time Distribution for Pedestrians

Original

Relative Häufigk. vs. Dauer der Rotzeiten in Sekunden

Online

Relative Häufigk. vs. Dauer der Rotzeiten in Sekunden
Gain in Performance

Öffentlicher Personenverkehr

2.02 Fzh

0.89 Fzh

-56%

Verlustzeiten

Kraftfahrzeuge

63.9 Fzh

58.5 Fzh

-9%

Verlustzeiten

Fußgänger und Radfahrer

59 s

38 s

-36%

Mittlere Sperrzeit
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.

(Logistic target achievement vs. Complexity vs. Level of autonomy of control)

(Windt, Böse, Philipp, 2006)
Thank you for your interest!
Any Questions?