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
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
At high densities, free traffic flow is unstable: Despite best efforts, drivers fail to maintain speed.
How to Analyze the Cross-Sectional Traffic Data

(a) Velocity (km/h)
(b) Velocity (km/h)
(c) Location (km)
(d) Location (km)

Time (h)
Time (h)

Accident
Accident
How the Adaptive Smoothing Method Works

\[ t'_{\text{cong}} = t - \frac{X}{c_{\text{cong}}} = \text{const.} \]

\[ t'_{\text{free}} = t - \frac{X}{c_{\text{free}}} = \text{const.} \]

\[ \phi (x-x_0, t-t_0) > \text{const'} \]

\[ \phi (x-x_0, t-t_0) > \text{const'} \]
Complex Congestion Patterns

(a) Velocity (km/h)

A5 South
04/09/2001
(Mon.)

Location (km)

(b) Velocity (km/h)

A5 North
04/20/2001
(Fri.)

Location (km)
Surprising Variety of Congestion Patterns
Congested Traffic States Simulated with a Macroscopic Traffic Model

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

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

\( Q_{\text{tot}} = Q_{\text{up}} + \Delta Q \)

- Always congested
- SGW, OCT

Phase diagram for large perturbations

\( Q_{\text{tot}} = Q_{\text{up}} + \Delta Q \)

- SGW, OCT
- HCT
- MLC
- PLC

After: PRL (1999)
Empirical Phase Diagram

(b) A5 South: Junction Friedberg

$Q_{up}$ (vehicles/h/lane)

$\Delta Q$ (vehicles/h/lane)
The Outflow Depends on the Weather Conditions

- Outflow $Q_{out}$ (veh/h/ lane)
- Range of Visibility (km)

Key:
- W: wet road
- (w): affected by showers
- D: dry road
Empirical Phase Diagram for Scaled Flows

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

Rottepolderplein S17

Badhoevedorp

43.31 km 42.25 41.75 40.80 39.60

37.60 36.90 36.60 35.89 km
(Intermittent) Activation of an Off-Ramp Bottleneck

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

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

A5 South, June 25, 2001

A5 North, April 11, 2001
An Analytical Theory of Traffic Flow

D. Helbing
Derivation of non-local macroscopic traffic equations and consistent traffic pressures from microscopic car-following models
DOI: 10.1140/epjb/e2009-00192-5

D. Helbing and A.F. Johansson
On the controversy around Daganzo’s requiem for and Aw-Rascle’s resurrection of second-order traffic flow models
DOI: 10.1140/epjb/e2009-00182-7

D. Helbing and M. Moussaid
Analytical calculation of critical perturbation amplitudes and critical densities by non-linear stability analysis of a simple traffic flow model
DOI: 10.1140/epjb/e2009-00060-6

Theoretical vs. empirical classification and prediction of congested traffic states
DOI: 10.1140/epjb/e2009-00070-5

A. Treiber and D. Helbing
Hamilton-like statistics in one-dimensional driven dissipative many-particle systems
DOI: 10.1140/epjb/e2009-00031-0

D. Helbing and B. Tilch
A power law for the duration of high-flow states and its interpretation from a heterogeneous traffic flow perspective
DOI: 10.1140/epjb/e2009-00090-8

D. Helbing
Derivation of a fundamental diagram for urban traffic flow
DOI: 10.1140/epjb/e2009-00080-7

D. Helbing and A. Matarzian
Operative regimes and slower-is-faster effect in the control of traffic intersections
DOI: 10.1140/epjb/e2009-00091-7
Freeway Traffic Control
Cooperative Driving Based on Autonomous Vehicle Interactions

- 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

Junction Friedberg
Accident 19:15
Intersection Bad Homburg

Velocity (km/h)
Statistics of Message Transmission

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

\[ P(T_2 < t) = \Theta \left( t - \frac{r_{up} - 2r}{v} \right) \left( 1 - e^{-\beta(2r+vt-r_{up})} \right) \]
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=208 s
8) Free traffic at x=3719 m, t=208 s
9) ...

Stop-and-Go Wave (Freeway totally blocked at x=3500 m from t = 60 s to t = 180 s)
Traffic-Adaptive Driving Strategy for ACC

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

**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)

**VLA Matrix for IDM**

<table>
<thead>
<tr>
<th>aVLA/a</th>
<th>bVLA/b</th>
<th>Tvl/a/T</th>
</tr>
</thead>
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<td>1.0</td>
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</tr>
<tr>
<td>2.0</td>
<td>1.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Downstream Bottom of Congestion**
Forceful and accurately timed acceleration most important
Overcoming Congestion by Real-Time Feedback
Enhancing Traffic Performance by Adaptive Cruise Control

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

ρ(veh./km/lane)

10% Equipped Vehicles

20% Equipped Vehicles

“Mechanism design”, in cooperation with Volkswagen
A Driver-Oriented Level of Service

Accident (Freeway A5 Aug, 4 2001)

Velocity (km/h)

Connector Friedberg

Accident (13:50h)

Connector Bad Homburger Kreuz

Graphs showing relative travel time, fuel consumption, and discomfort over time.
Travel Demand
Zahavi and others: People spend about 1 hour traveling (on average), and they do it since ages. There is a fixed travel time budget.

Is Zahavi’s Theory of a Constant Travel Time Budget Correct?
Constant Travel Time Budget Is an Urban Legend!

The Travel Time Budget Is Not a Constant

![Bar graph showing average daily travel time budget in different cities: Roma, Palermo, Genova, Napoli, Bari, Milano, Torino, Bologna. Roma has the highest average daily travel time budget, followed by Palermo and Genova, while Bologna has the lowest.]
Living Costs and Public Transport Determine Travel Time Budget

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.)
Comparing 3 Ways to Organize a Complex System

- **Optimal top-down regulation**
  - Central control, "benevolent dictator"

- **Bottom-up self-organization**
  - Travel time minimization, "homo economicus"

- **Bottom-up self-regulation**
  - Same, but other-regarding coordination with neighbors
Bottom-Up Self-Regulation Can Outsmart Optimal Top-Down Control
Bottom-Up Self-Regulation Can Outsmart Optimal Top-Down Control

Top-down regulation

Clearing longest queue

Selfish optimization, self-organization

Queue length

Capacity utilization

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

Adam Smith’s invisible hand works

Top-down regulation

Selfish optimization, self-organization

Clearing longest queue

Queue length vs. Capacity utilization graph
Bottom-Up Self-Regulation Can Outsmart Optimal Top-Down Control

Adam Smith’s invisible hand fails

Selfish optimization, self-organization

Top-down regulation

Clearing longest queue

Queue length

Capacity utilization

over-saturated

0 0.2 0.3 0.4 0.5 0.6 0.7 0.8

0 5 10 15 20 25 30 35

0 1 2 3 4 5 6 7 8

D GESS

Stefan Lämmer and Dirk Helbing
Bottom-Up Self-Regulation Can Outsmart Optimal Top-Down Control

- Top-down regulation
- Selfish optimization, self-organization
- Clearing longest queue
- Other-regarding optimization, self-regulation

Stefan Lämmer and Dirk Helbing
Bottom-Up Self-Regulation Can Outsmart Optimal Top-Down Control

Invisible hand works
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)
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

- Public transport: 2.02 vh, 0.89 vh, -56%
- Motorized traffic: 63.9 vh, 58.5 vh, -9%
- Pedestrians and Cyclists: 59 s, 38 s, -36%

Total delay
Production, Supply Chains, and Logistics as Traffic Problems
**Analogy to Production Networks**

### Road Networks vs. 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
Analyses of Production with Traffic Dynamics

1. Bottleneck develops

2. a. Jam propagates upstream

2. b. Missing quantities grow downstream
Long breakdown starts at inventory level of 60%.

First machine has to wait after 5.5 hrs (> mean value + 2 • std.dev. of TTR)

Last machine has to wait (after 25 hrs).
John D. Sterman’s Beer Game

Perturbations in demand amplify

Dirk Helbing, Professor of Computational Social Science
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

\[ \dot{N}_i(t) = Q_i(t) - \sum_{j=1}^{m} a_{ij} Q_j(t) - Y_i(t) \]

- supply
- re-entrant
- outflow

Adaptation of delivery rates

\[ \frac{\dot{Q}_i(t)}{Q_i(t)} = \dot{\nu} \left( \frac{N_i^0}{N_i(t)} - 1 \right) - \dot{\mu} \frac{\dot{N}_i(t)}{N_i(t)} \]

- deviations from desired level
- temporal changes

Adaptation of prices

\[ \frac{\dot{P}_i(t)}{P_i(t)} = \nu \left( \frac{N_i^0}{N_i(t)} - 1 \right) - \mu \frac{\dot{N}_i(t)}{N_i(t)} \]

- deviations from desired level
- temporal changes

Consumption

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

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

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

Redundancy Matters: Distribution Network of Intel Technologies

- **Ven.** = Vendors
- **= Inventory**
- **= Plants**
- **= Transport**

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
Specification of Information Flows and Interaction Rules

1. A unit enters the lane
2. It decides to exit the lane
3. It sends a request for a transfer car
4. The unit exits the lane
Alternative Paths: Interaction-Based Routing

Possible paths:

Machine with input buffer as sink

Machine with output buffer as source
A New Paradigm
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).

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

\[
\frac{dv_\alpha}{dt} = \frac{1}{\tau_\alpha} (v^{0}_\alpha e^{0}_\alpha - v_\alpha) + \sum_{\beta(\neq \alpha)} F^{\text{int}}_{\alpha\beta} + F^{\text{walls}}_{\alpha} \quad \text{(acceleration equation)}
\]
Experimental Study of Individual Avoidance Behavior

Avoidance of a static pedestrian

Avoidance of a moving pedestrian
Validation 1: Corridor Experiment

**Observed and simulated pedestrian trajectories**

- **Standing**:
  - Preferences: Side

- **Moving**:
  - Preferences: Side

(b1) and (b2) show the distribution of preferred sides for standing and moving respectively.
Validation 2: Collective Dynamics

Observations in a crowded street
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!

Video-recorded area

Bottleneck
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

FuturiICT

www.futurict.eu
Building a Planetary Nervous System for Real-Time Measurements

Dirk Helbing and team
Planetary Nervous System (PNS)

Transform data from the globe spanning ICT system into information about the state of the world.

Public mood

Usage patterns

Mobility patterns

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
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!
The „Internet of Things“ as Citizen Web

A Participatory System

Dirk Helbing, Professor of Computational Social Science
An Open Data Source, but Real Time
With A Micro-Payment System...
...You Can Run Your Own Business...

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

IDEAS FRESCAS

PROSUMERS
PRODUCERS + CONSUMERS

participatory culture and the empowered media prosumer

search
delicious (annotate, leave trail)
consumption

team, performance
curate, play

production

by Eli Chapman
3/10/05
http://www.chapmanlogic.com/blog

D GEES
Let's Do This Together!
Create Our Own Open Data

“Give and take is fair play.”

English Proverb
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
Map Environmental Change and Who Causes It

Border between Haiti and Dominican Republic
Map Resources and Who Uses Them

Would help to avoid shortages and recessions

From http://www.yanmar-e.co.jp/service/index.html
Map Conflicts and How They Come About

Joint work of Thomas Chadeaux and Dirk Helbing

Dirk Helbing, Professor of Computational Social Science
Get Ready!

https://ampaiipse.wordpress.com/page/2/
Team Up With Your Friends + Colleagues
Join the nervousnet Community