From Traffic Flows to Pedestrian Crowds to Social Cooperation

Dirk Helbing et al.
Computational Social Science (www.coss.ethz.ch)
Auguste Comte (1798-1857)
is often called the “father” of sociology. He proposed a rational
(“positivistic”) approach to the study of society, based on
observation and experiment. In the beginning, he called his
approach “social physics”, but later he used the term “sociology”
(meaning knowledge of society).
Auguste Comte considered sociology to be the queen of sciences.
Comparing, for example, sociology with biology and physics, the
systems it deals with are the most complex ones.
Will Computational Social Science deliver the breakthroughs?
Many social systems are so complex, that the relevant variables and parameters involved are hard to identify and to measure. I will, therefore, study a few simple, measurable systems (leaving, for the time being, complex issues like meanings, values, historical aspects, and other behavioral dimensions aside), hoping that one can learn something more general from the principles observed in these examples.

George Box: “All models are wrong. (But some are useful.)”

Josh Epstein: “If you didn’t grow it, you didn’t explain it.”

The more parameters a model has, the more difficult it is to fit them all exactly. This may affect the accuracy of predictions.
Do Simple Models Work? Also for Social System?

Geocentric Picture: Epicycles around the Earth

Heliocentric Picture: Elliptical paths around the sun
Cascading Effects During Financial Crises

Social Dilemma Problem
- Global Warming
- (Financial Crisis)
- Free-Riding
- Tax Evasion
- Environmental Pollution
- Environmental Exploitation
- Overfishing

“Tragedies of the Commons”, e.g. Overfishing
Some Observations: “Phantom Traffic Jams“
Understanding the Complexity of Traffic Dynamics on Freeways

Dirk Helbing

with Martin Treiber, Arne Kestling, Stefan Lämmer, Martin Schönhof, and others
Instability of Traffic Flow: Stop-and-Go Waves
At first sight, developing a theory of traffic flow seems hopeless!

Can We Understand Traffic Flows?
The Complexity of Traffic Flow Can Be Reduced to Some Elementary 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.

Intelligent-Driver Model (IDM)

Equations of motion:

\[ \dot{v}_\alpha = v_\alpha, \]

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

Dynamic desired distance:

\[ s^*(v, \Delta v) = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}} \]
Phase Diagram of Traffic States and Universality Classes

Phase diagram for small perturbations

Phase diagram for large perturbations

After: *PRL* (1999)
M = MLC = moving localized cluster, P = PLC = pinned localized cluster
O = OCT = oscillating congested traffic, S = SWG = stop-and-go waves
H = HCT = homogeneous congested traffic
Traffic Congestion and Travel Times Are Predictable
An Analytical Theory of Traffic Flow

D. Helbing
Derivation of non-local macroscopic traffic equations and conслatant 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/e2009-00163-7

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/e2009-00042-6

Theoretical vs. empirical classification and prediction of congested traffic states.
DOI: 10.1140/epjb/e2009-00121-8

M. Treiber and D. Helbing
Hamilton-like statistics in one dimensional driven dissipative many-particle systems.
DOI: 10.1140/epjb/e2009-00121-8

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/e2009-00092-8

D. Helbing
Derivation of a fundamental diagram for urban traffic flow.
DOI: 10.1140/epjb/e2009-00093-7

D. Helbing and A. Mazloumian
Operation regimes and slower-is-faster effect in the control of traffic intersections.
DOI: 10.1140/epjb/e2009-00213-5
Self-Organized Cooperative Driving

- 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)
Dissolving Traffic Jams with A Traffic Assistance System
With Suitable Feedback Loops, A Complex Dynamical System Self-Organizes Like Magic
Pedestrian, Crowd, and Evacuation Dynamics

Dirk Helbing

with Anders Johansson, Wenjian Yu, Mehdi Moussaid, Illes Farkas, Peter Molnar, Tamas Vicsek and others
Emergent Collective Behavior by Human Interactions

What is interesting about social systems is the emergence of new, functional or complex system behaviors, particularly cooperation or coordination patterns based on elementary individual interactions.

For example, lanes of uniform walking direction emerge due to self-organization.

Preference of right-hand side is a convention, which can be understood by evolutionary game theory, as the payoff is larger for individuals who follow the majority behavior (B. Arthur’89/A. Rapoport’93)
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). It is composed of the following forces:

- Driving forces (to maintain the desired walking direction and speed)
- Social repulsive forces (to keep a private sphere around oneself)
- Social attractive forces among group members
- Repulsive forces reflecting the influence of walls
- Fluctuation forces describing variations in behavior

\[
\begin{align*}
\frac{dx_\alpha}{dt} &= v_\alpha(t) \quad \text{(equation of motion)} \\
\frac{dv_\alpha}{dt} &= \frac{1}{\tau_\alpha} (v_\alpha^0 e_\alpha^0 - v_\alpha) + \sum_{\beta(\neq \alpha)} F^{\text{int}}_{\alpha \beta} + \frac{F^{\text{walls}}_{\alpha}}{\text{boundaries}} \quad \text{(acceleration equation)}
\end{align*}
\]

As people show a pretty standard behavior in walking interactions and constrain each others’ motion, the dynamics of crowds can be relatively well predicted.
Elliptical Social Force Model

An improved, elliptical, specification of the social force model has been proposed, taking into account velocity and relative velocities. $\Delta t$ reflects the time for a stride and $b$ is the semi-minor axis of an ellipse directed into the direction of motion:

Repulsive potential:
$$V_{\alpha\beta}(b) = AB e^{-b_{\alpha\beta}/B}$$

Elliptical specification I:
$$2b = \sqrt{\left(\|\vec{d}_{\alpha\beta}\| + \|\vec{d}_{\alpha\beta} - v_\beta \Delta t \vec{e}_\beta\|\right)^2 - (v_\beta \Delta t)^2}$$

Elliptical specification II:
$$2b = \sqrt{\left(\|\vec{d}_{\alpha\beta}\| + \|\vec{d}_{\alpha\beta} - (\vec{v}_\beta - \vec{v}_\alpha) \Delta t\|\right)^2 - [(\vec{v}_\beta - \vec{v}_\alpha) \Delta t]^2}$$
Empirical Evaluation of Pedestrian Trajectories

Calculate trend matrices:
Trend_0 = Frame_n - Frame_{n-1}
Trend_1 = Frame_{n-1} - Frame_{n-2}

Recognize movement by searching for similarities in the local neighborhoods around each point in the trend matrices.

Transform the trajectory coordinates into the ground plane, by approximating each human to be 170 cm high.
Calibration with Genetic Algorithms

We use a hybrid model where n-1 of the n pedestrians are moving according to the trajectories from the videos, and 1 pedestrian is controlled by a micro-simulation. Then we have an error measure related to the deviation from our simulated position and the actual position from the video. With this error measure we can iterate a calibration process that will find an optimal set of simulation parameters.

<table>
<thead>
<tr>
<th>Model</th>
<th>A</th>
<th>B</th>
<th>λ</th>
<th>Fitness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>0.11 ± 0.06</td>
<td>0.84 ± 0.63</td>
<td>1</td>
<td>-0.65</td>
</tr>
<tr>
<td>Elliptical I</td>
<td>1.52 ± 1.65</td>
<td>0.21 ± 0.08</td>
<td>1</td>
<td>-0.67</td>
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<tr>
<td>Elliptical II</td>
<td>4.30 ± 3.91</td>
<td>1.07 ± 1.35</td>
<td>1</td>
<td>-0.47</td>
</tr>
<tr>
<td>Circular</td>
<td>0.42 ± 0.26</td>
<td>1.65 ± 1.01</td>
<td>0.12 ± 0.07</td>
<td>-0.60</td>
</tr>
<tr>
<td>Elliptical I</td>
<td>0.11 ± 0.01</td>
<td>1.19 ± 0.45</td>
<td>0.16 ± 0.04</td>
<td>-0.59</td>
</tr>
<tr>
<td>Elliptical II</td>
<td>0.04 ± 0.01</td>
<td>3.22 ± 0.67</td>
<td>0.06 ± 0.04</td>
<td>-0.39</td>
</tr>
</tbody>
</table>
The distance-dependent function is investigated at the distances, 0m, 0.5m, 1m, ..., 4.5m, and when fitting these values with the videos (black curve) it matches very well to an exponential function (blue dotted curve).
Angular Dependence

Similarly to how the distance-dependent function was obtained, we fit a polygon with 32 points distributed around each pedestrian, at fixed angles. When calibrating to the videos, it turns out that the angular dependence can be approximated with a half circle around the pedestrian.

\[
w(\varphi_{\alpha\beta}(t)) = \left(\lambda_{\alpha} + (1 - \lambda_{\alpha}) \frac{1 + \cos(\varphi_{\alpha\beta})}{2}\right)
\]

Polygons obtained from videos
Experimental Approach

- Individual Behavior
- Collective Dynamics

Quantitative data

Model

Quantitative data

§

Individual Behavior

Collective Dynamics
Individual Acceleration Behavior

Setup 1

Single pedestrian’s behavior

Average walking speed of single pedestrians
Individual Avoidance Behavior

Setups 2 & 3

Avoidance of a static pedestrian

Avoidance of a moving pedestrian
Side Choice Asymmetry Is Amplified by Mutual Adaptation
Empirical Force Field

- Repulsive field in front of a pedestrian
  - Front area: Speed decrease
  - Sides areas: Directional change
Comparison of Observations and Simulations
Validation 1: Corridor Experiment

Quantitative validation

Average observed trajectory + std

Average simulated trajectory
Validation 2: Collective Dynamics

Observations in a crowded street
Based on individual interactions, lanes of uniform walking directions emerge in pedestrian crowds by self-organization. This constitutes a "macroscopic" social structure. Nobody orchestrates this collective behavior, and most people are not even aware of it.
Oscillatory Pedestrian Flows at Bottlenecks
Stripe Formation
Studying More Realistic and Complex Scenarios
Social Force Model - Corners
Social Force Model - Complex Environments
Rimea Scenarios - Evacuation of a Hotel
Large-Scale Simulation of Mass Events and Urban Areas

iterations: 0, time=0.000 s, pedestrians=0, satisfied=0
The computational speed of the original social-force model is $O(n^2)$ for the number of pedestrians $n$.

The social-force model implementation in VISSIM however, is scaling $O(n)$, i.e. linearly in the number of pedestrians, which makes it suitable for large-scale simulations.
Social Force Model – Putting Everything Together
How to Improve Pedestrian Facilities
How to Optimize Pedestrian Facilities

Conventional  Improved

Diagram showing conventional and improved pedestrian facilities.
Practical Implications and Design Solutions for Intersections

Conventional
- unstable, chaotic flow
- counter-flow

Improved
- barriers
- obstacle stripes
- uni-directional flow
- circular flow

Dysfunctional
- barriers
- obstacle stripes
- uni-directional flow

Space-Saving Design
- railings
- obstacle stripes
- uni-directional flow
- circular flow
Evolutionary Optimization of Pedestrian Facilities

Original Multiplication

Selection

Evaluation
Performance Criterion: Efficiency

\[ E = \frac{1}{N} \sum_{\alpha} \frac{\bar{v}_a(t) \cdot \bar{e}_a}{v^0_\alpha} \]

Mutation (Random Variations)

Test (Simulation)
Evolutionary Optimization of a Bottleneck
Typical Evolutionary Designs (Preliminary)

Snapshot; without obstacles

Zig-zag shape (fitness 1.78)

Snapshot; with obstacles

Funnel shape (fitness 1.99)
Safety Assessment of Architectural Designs

Conventional

Improved
Slower-Is-Faster Effects and Role of Obstacles

Without an obstacle one can observe clogging effects and a tendency of people to fall in panic situations (left).

The clogging effect can be significantly reduced by a suitable obstacle, which increases the efficiency of escape and diminishes the tendency of falling (right).
Crowd Disasters
Breakdown of Coordination: Crowd Disasters

At low densities:
self-organized lane formation,
like Adam Smith’s invisible hand

At large densities: coordination breaks down

Love Parade Disaster in Duisburg, 2010
Why do crowd disasters happen, even if nobody wants to harm anybody else?

Are crowd disasters a result of people, who start panicking, for whatever reason?
Role of Fluctuations

Small Fluctuations: Lane Formation

Large Fluctuations: “Freezing by Heating”

Ensemble-Averaged Efficiency

Reminder: The temperature is proportional to the velocity variance.

Case Study:
The Muslim Pilgrimage in Mecca
The Jamarat Bridge (as of January 2006)

Elliptical shape to avoid crushing
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 vehicle traffic!
Competition for a scarce resource, here: space.

This leads to intermittent outflows with periods of no outflow. High-density clusters break up irregularly. The sizes of groups leaving the bottleneck together vary largely. Stop-and-go waves are a result.

At high densities, several people may compete for the same gap and block each other. This constitutes a conflict and causes an alternation between downstream pedestrian and upstream gap propagation.
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”
The New Jamarat Bridge and Its Advantages

- In conjunction with appropriate management, the proposed new Jamarat Bridge design results in meaningful improvements in safety over existing conditions, in view of the overall design approach that supports
  - a segregation of pedestrian flow and vehicular traffic
  - a distribution of pilgrims to several entrances and channeling from origin area via ramps
  - elliptically shaped Jamarahs, which provide a greater perimeter than the current circular basin, hence better utilization, higher throughput and better opportunity for process management
  - additional space and better design features in the multi-storied structure
  - better provisions for service and incident relief operations.
One-Way Plaza Organization

Source: D. Serwill, IVV Aachen
Scheduling, Flow Monitoring and Adaptive Rerouting

Some possibilities for adaptive rerouting

Flow Monitoring

Scheduling
Congestion patterns are self-organization phenomena resulting from systemic instability (amplification and cascading effects).

When traffic breaks down, the freeway capacity is reduced.

Traffic assistance systems can change the interactions among cars (mechanism design) to stabilize traffic flows and increase capacity.

Real-time feedback is the way to make self-organization work such that desirable outcomes result. Hence, digital assistants can help.

In bidirectional pedestrian flows, one observes lane formation.

At bottlenecks, oscillatory walking directions may occur.

In two intersecting flows, stripe formation may occur, allowing people to walk through the other flow without stopping.

Crowd turbulence occurs when physical forces are transmitted between many pedestrian bodies. It may cause crowd disasters.

Mechanism design can help solve social problems such as tragedies of the commons, which are also based on systemic instability.
Further Reading


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