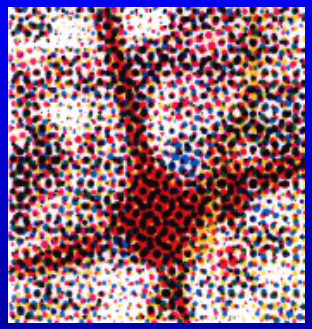
Self-Organization and Traffic Dynamics

Organic Computing, Bochum, 20 February 2009

Prof. Dr. Michael Schreckenberg
Physics of Transport and Traffic
Universität Duisburg-Essen

Physics of Transport and Traffic



Since 1997 at the University of Duisburg-Essen

10 Coworkers

Study: Physics of Transport and Traffic

Topics: Analysis, Modeling, Simulation
und Optimization of Transport Systems

Physics of Transport and Traffic

Topics:

- Road Traffic
- Railway Traffic
- Intelligent Transport Systems
- Traffic Forecast
- Evacuation Processes
- Inland-Shipway-Traffic
- Air Traffic
- Education!

The „Problem“

„All bad luck of the human beings stems from the fact, that they are not able to stay calmly in a room“

(Blaise Pascal, Pensée, 1640)


Fun
Mansion.com

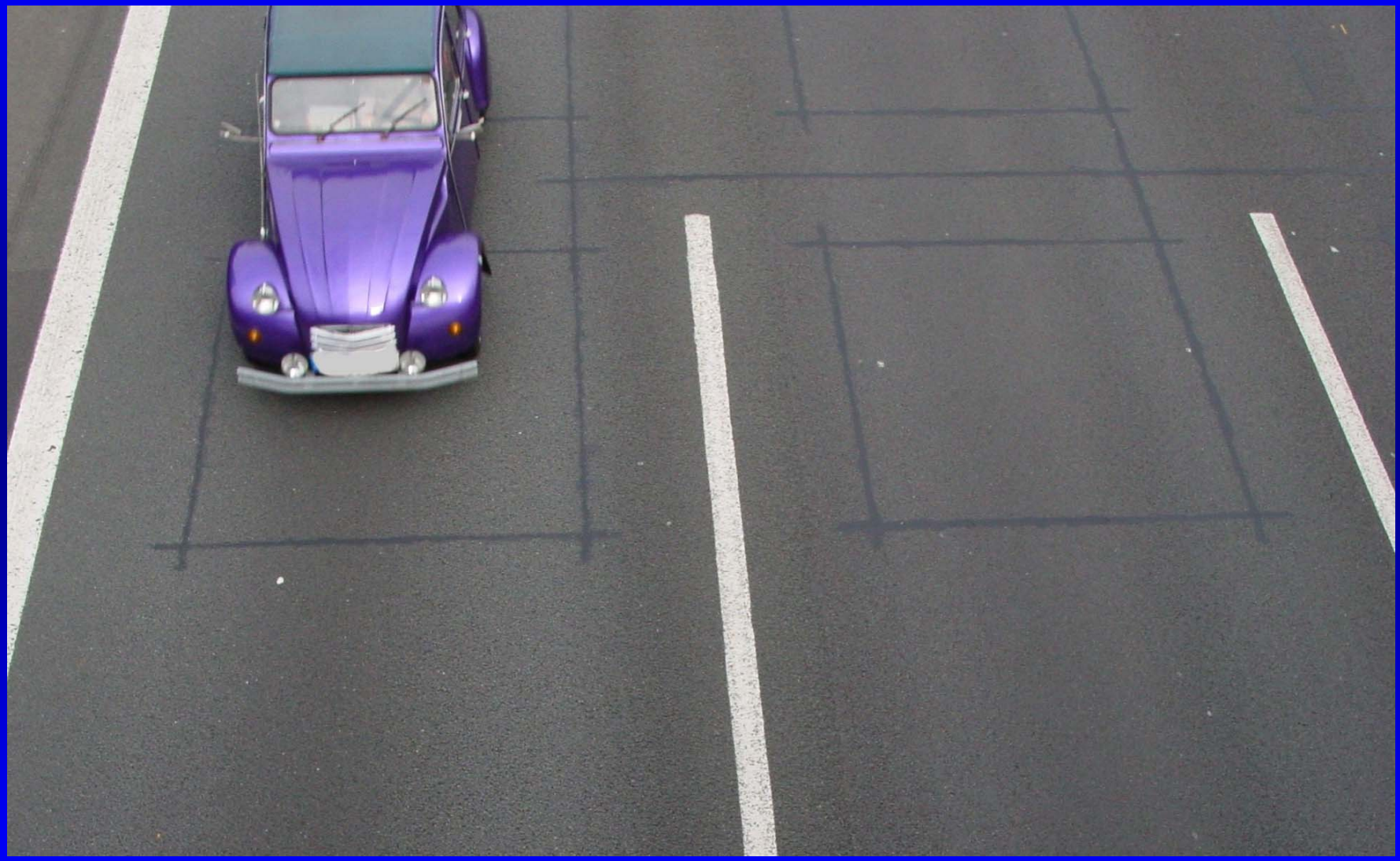
Tokai TV

A3 North at the Intersection Duisburg-Kaiserberg

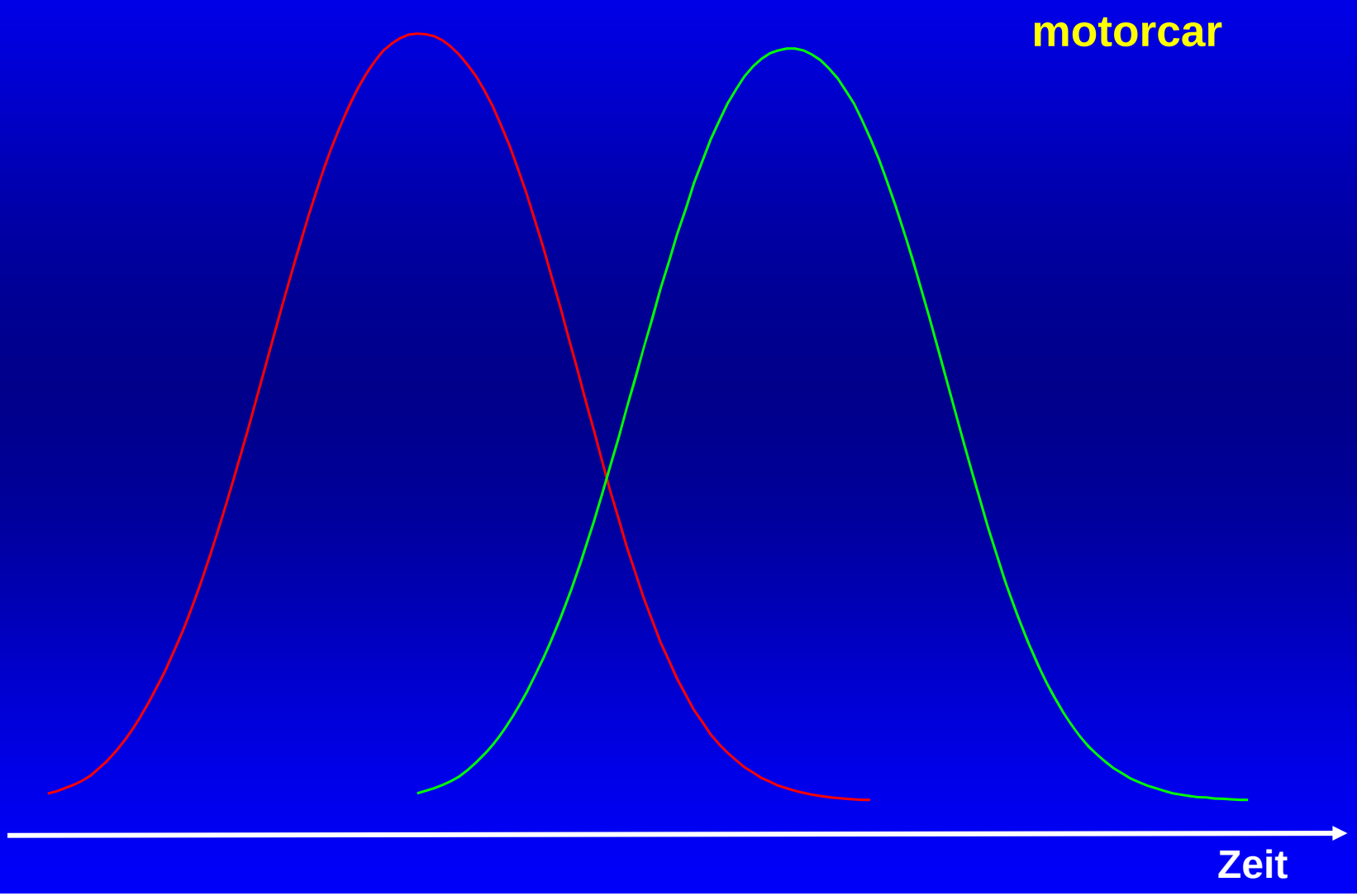
Traffic Data Detection

- Inductive loops
- Radar sensors
- Traffic eyes (infrared)
- Video
- Floating cars / cellular phone (location)
- Air photography / video (plane, zeppelin, hot-air ballon, satellite)

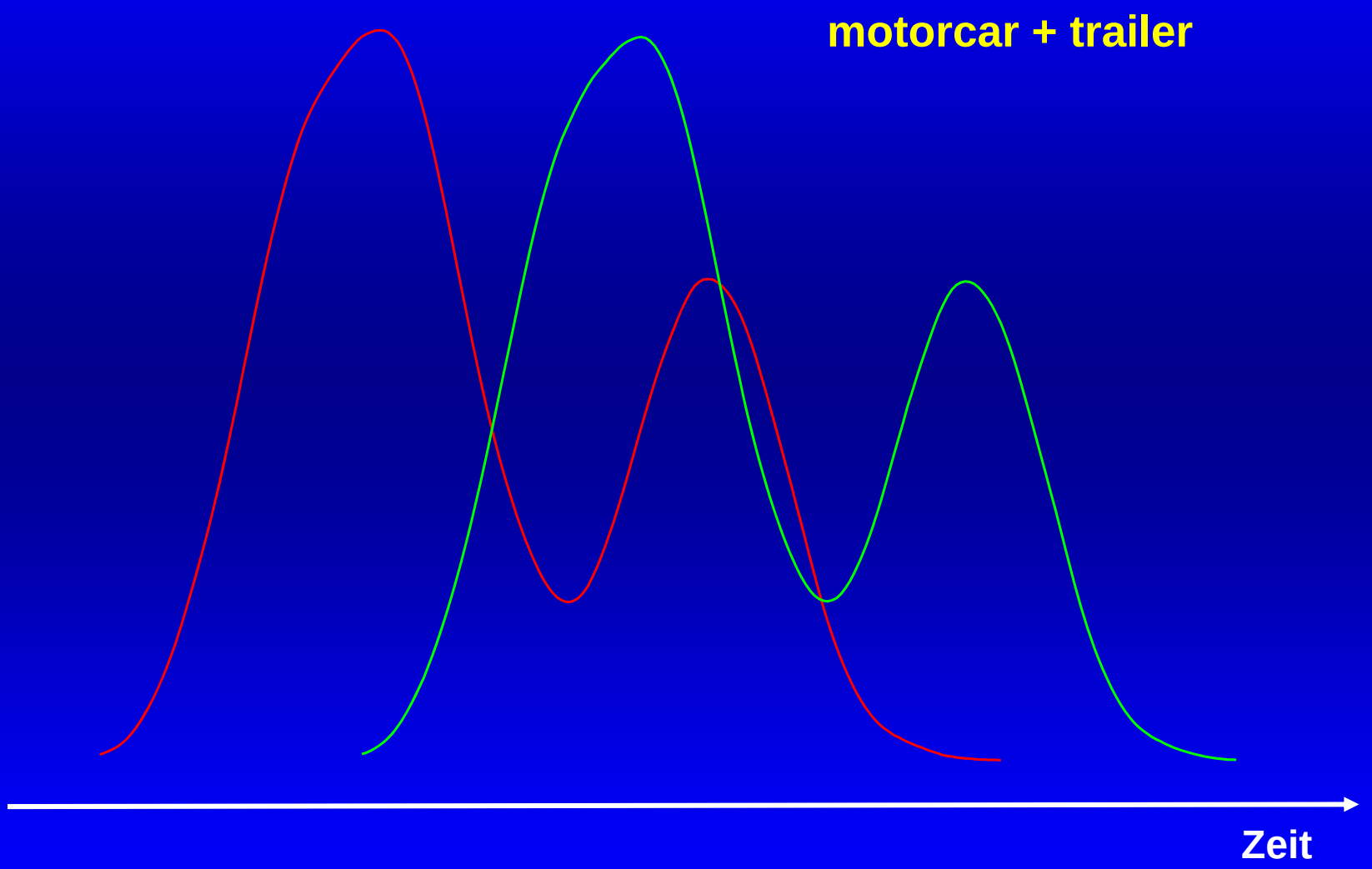
Inductive Loops



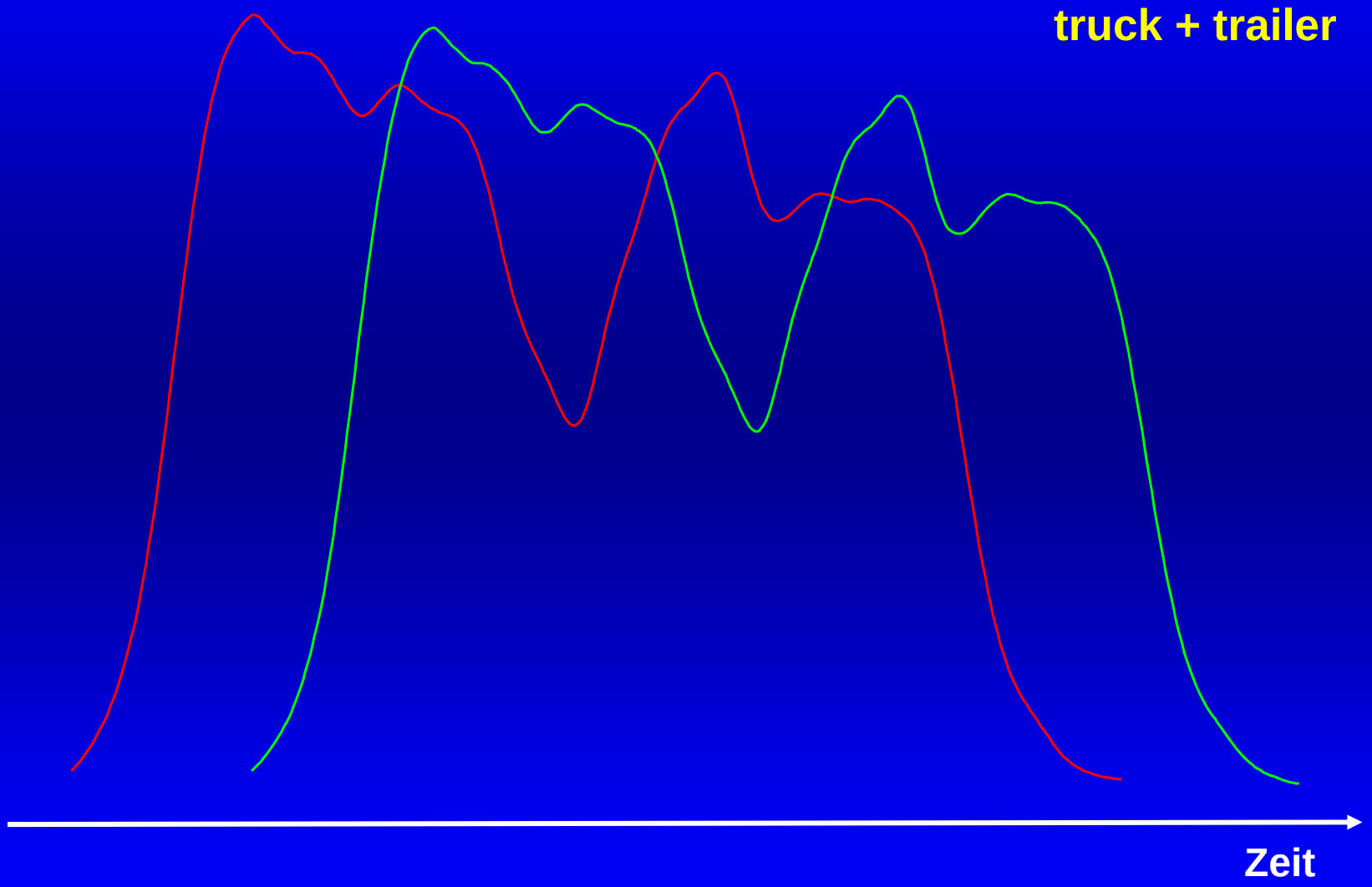
Signatures I



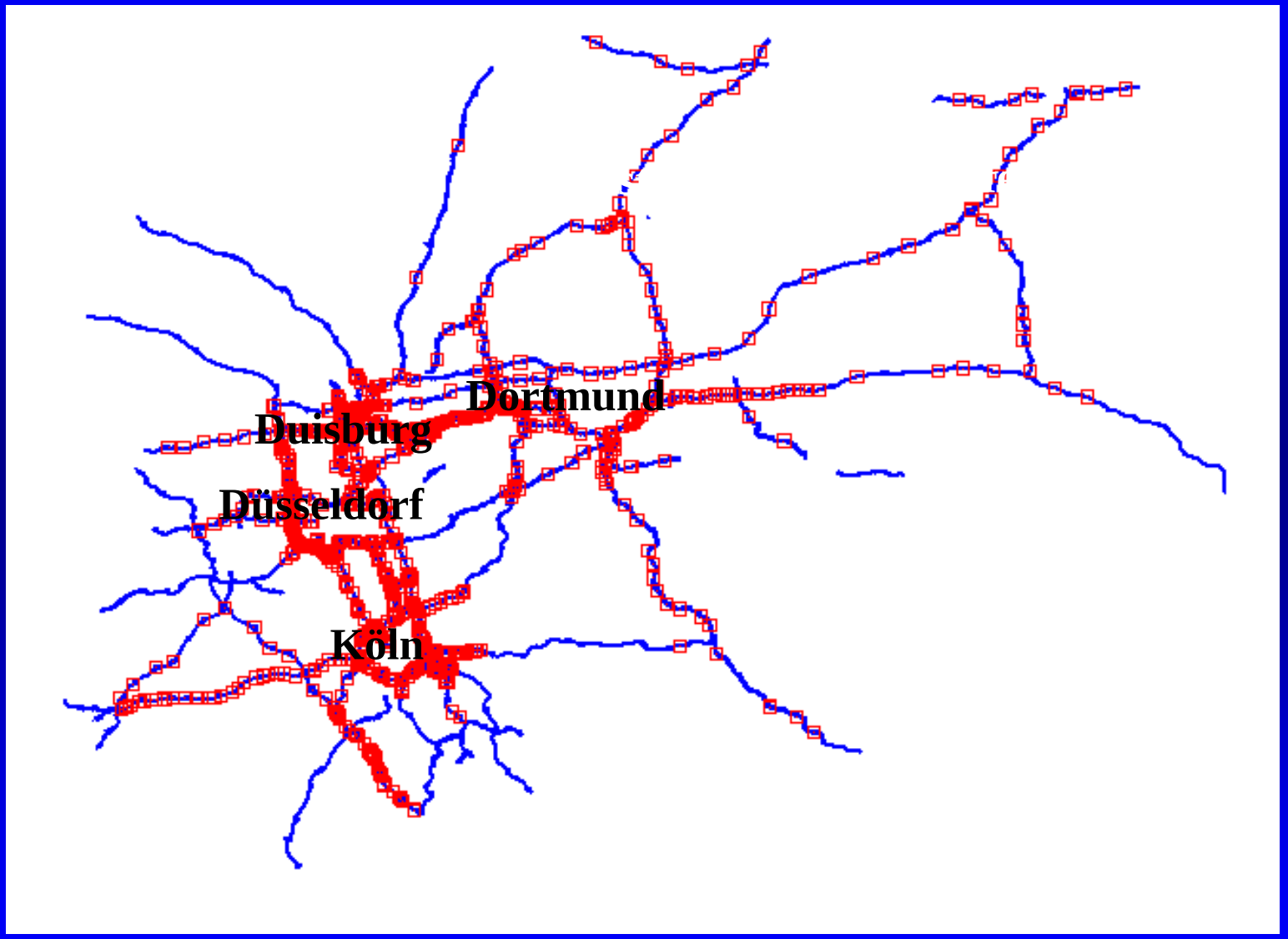
Signatures II



Signatures III



Inductive Loops in the Highways of NRW



Data Format

20020915 30 8 1 105 84 73 1 21 100
20020915 31 5 0 104 0 119 0 12 102
20020915 32 11 2 100 83 53 2 14 88
20020915 33 8 0 103 0 74 0 11 103
20020915 34 6 1 100 80 97 2 13 100
20020915 35 8 2 103 85 74 1 18 110
20020915 36 6 0 96 0 99 0 2 98
20020915 37 6 0 96 0 99 0 2 98
20020915 38 7 0 95 0 85 0 14 100
20020915 39 8 4 107 89 72 3 19 109
20020915 40 8 4 107 89 72 3 19 109
20020915 41 12 1 104 64 48 2 15 96
20020915 42 4 0 97 0 149 0 9 96
20020915 43 6 1 97 87 98 1 6 95
20020915 44 7 0 97 0 85 0 8 97
20020915 45 8 1 103 90 73 2 8 98
20020915 46 8 1 103 90 73 2 8 98
20020915 47 3 0 100 0 199 0 14 95
20020915 48 7 1 98 91 84 1 13 94
20020915 50 7 0 106 0 85 0 13 103
20020915 51 5 0 95 0 119 0 12 93
20020915 52 11 3 95 79 52 3 14 81
20020915 53 13 2 104 86 45 2 13 106
20020915 54 4 0 111 0 148 0 28 108
20020915 55 6 2 95 87 98 1 8 93
20020915 56 9 0 94 0 65 1 4 96
20020915 57 6 0 99 0 99 0 14 96
20020915 58 3 0 98 0 199 0 18 97
20020915 59 5 0 104 0 118 0 8 103
20020915 60 4 0 107 0 149 0 17 104
20020915 61 4 1 91 81 148 1 13 89
20020915 62 7 0 101 0 85 0 10 101
20020915 63 1 1 0 89 254 0 255 98
20020915 65 5 1 101 92 118 1 14 97
20020915 64 5 1 101 92 118 1 14 97
20020915 66 8 1 100 86 73 2 16 93
20020915 67 5 1 100 92 118 1 13 97
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20020915 69 7 0 89 0 84 1 9 92
20020915 70 6 1 104 97 99 0 8 101
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20020915 76 7 0 108 0 85 0 16 105
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20020915 86 7 4 102 93 83 2 9 96
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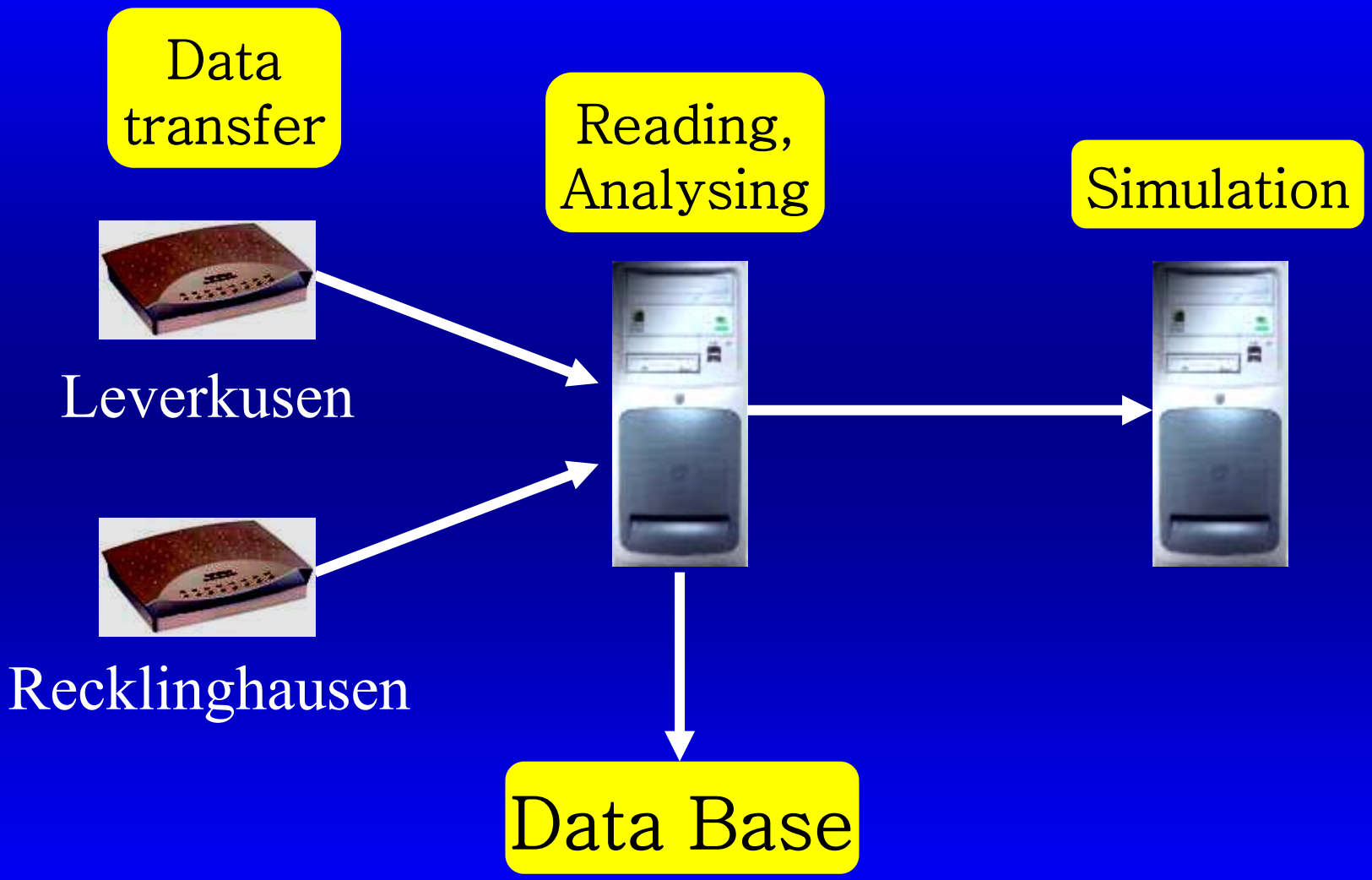
Data Transfer



The Energy Problem

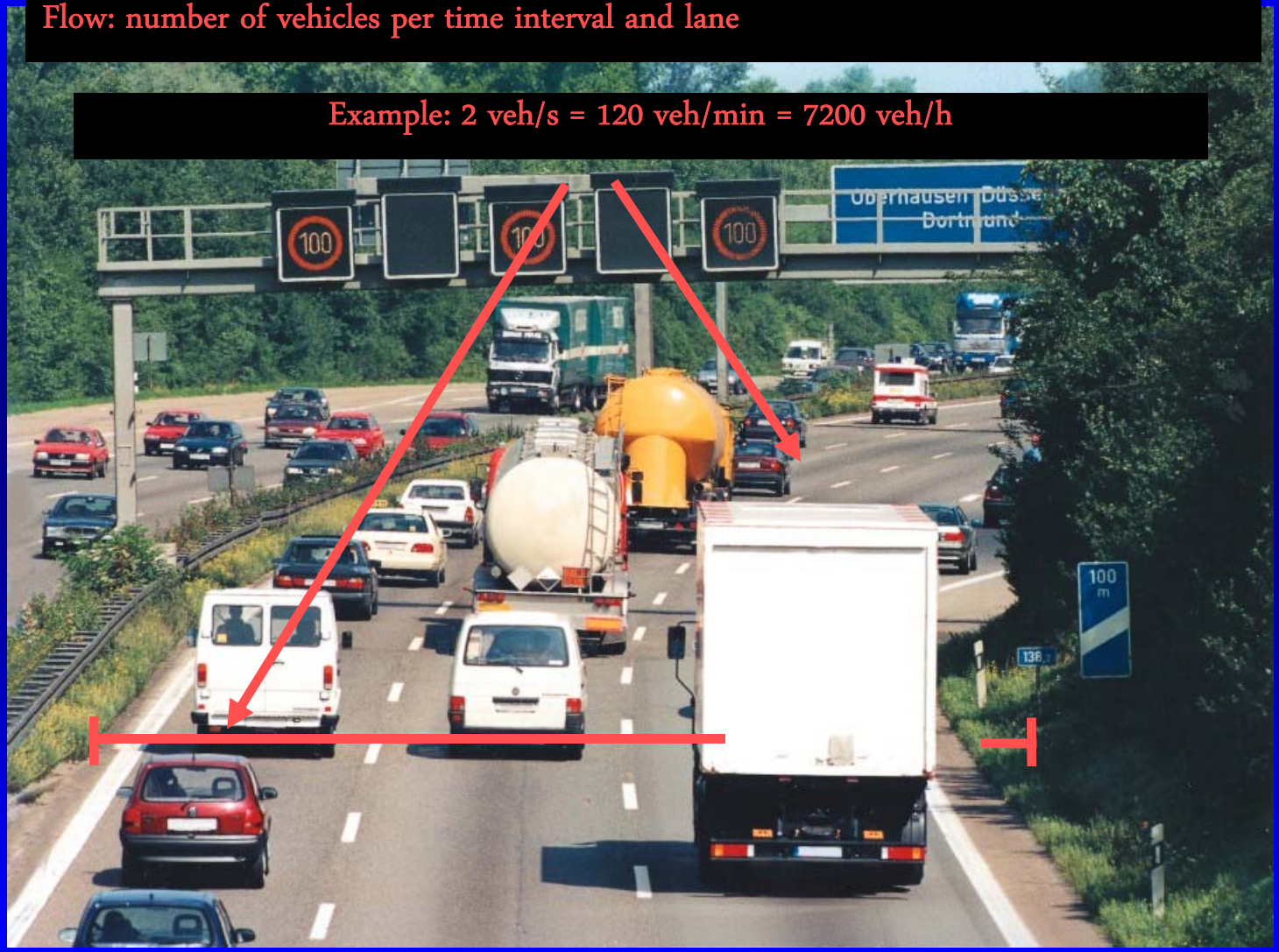
- Oil (ltd)
- Natural gas (ltd)
- Solar car (slow)
- Electric car (losses?)
- Water-diesel mixture (not stable)
- Fuel cell (hydrogen is only energy carrier! (80% loss))
- Rape (monoculture)
- Methanol (natural gas)
- Ethanol (rape, sugar cane / beet))
- Human power

Traffic Data: Example of Inductive Loops

Traffic Data: Example of Inductive Loops

Flow: number of vehicles per time interval and lane

Example: 2 veh/s = 120 veh/min = 7200 veh/h



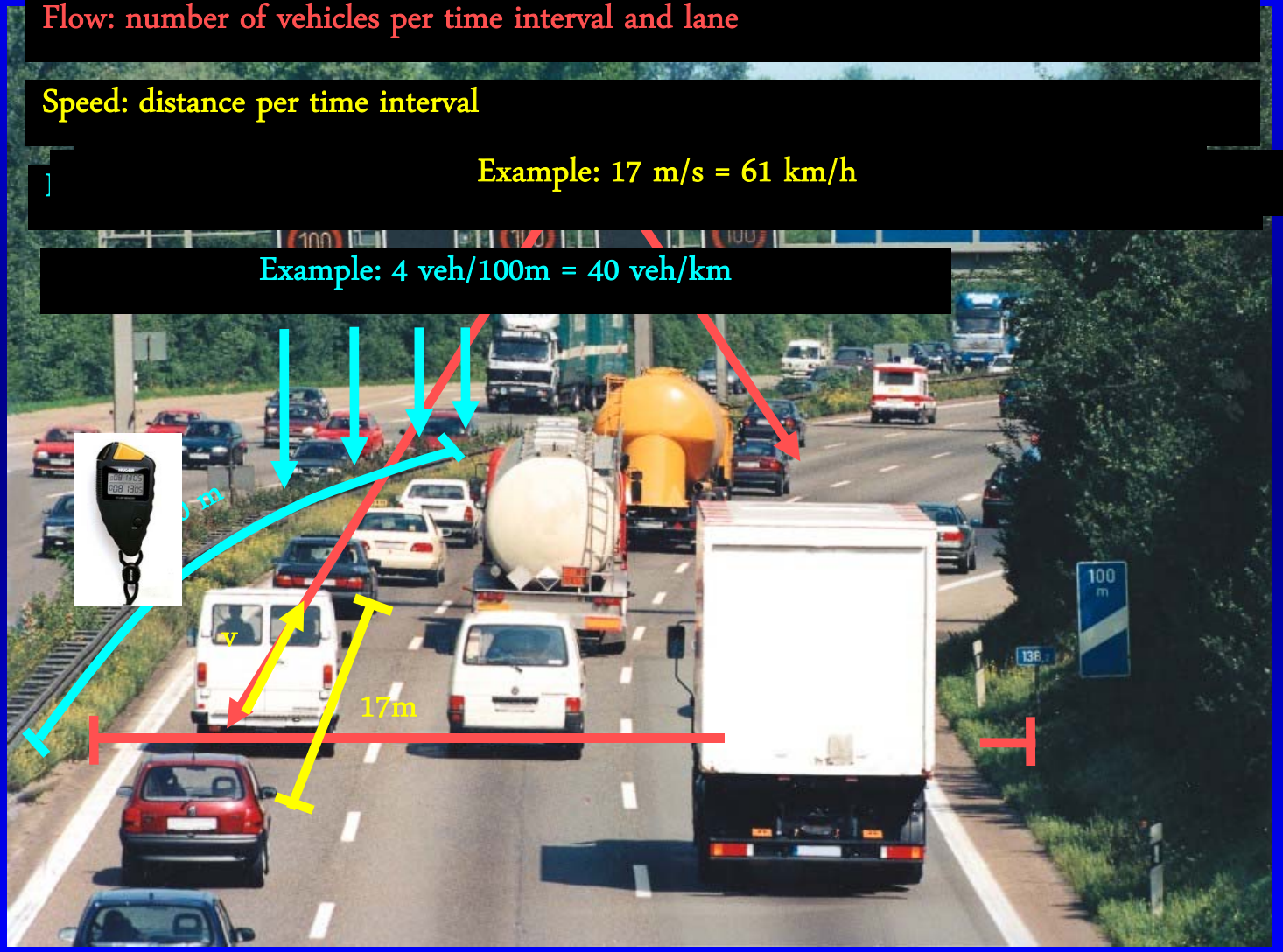
Traffic Data: Example of Inductive Loops

Flow: number of vehicles per time interval and lane

Speed: distance per time interval

Example: 17 m/s = 61 km/h

Example: 4 veh/100m = 40 veh/km



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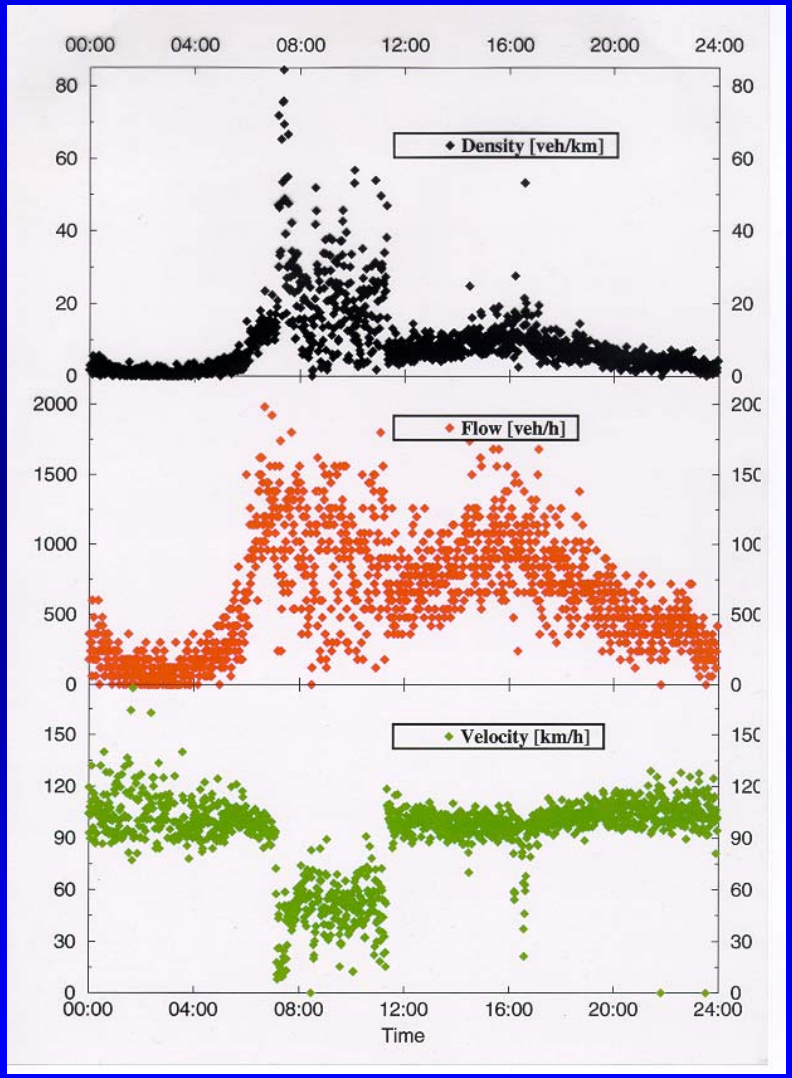
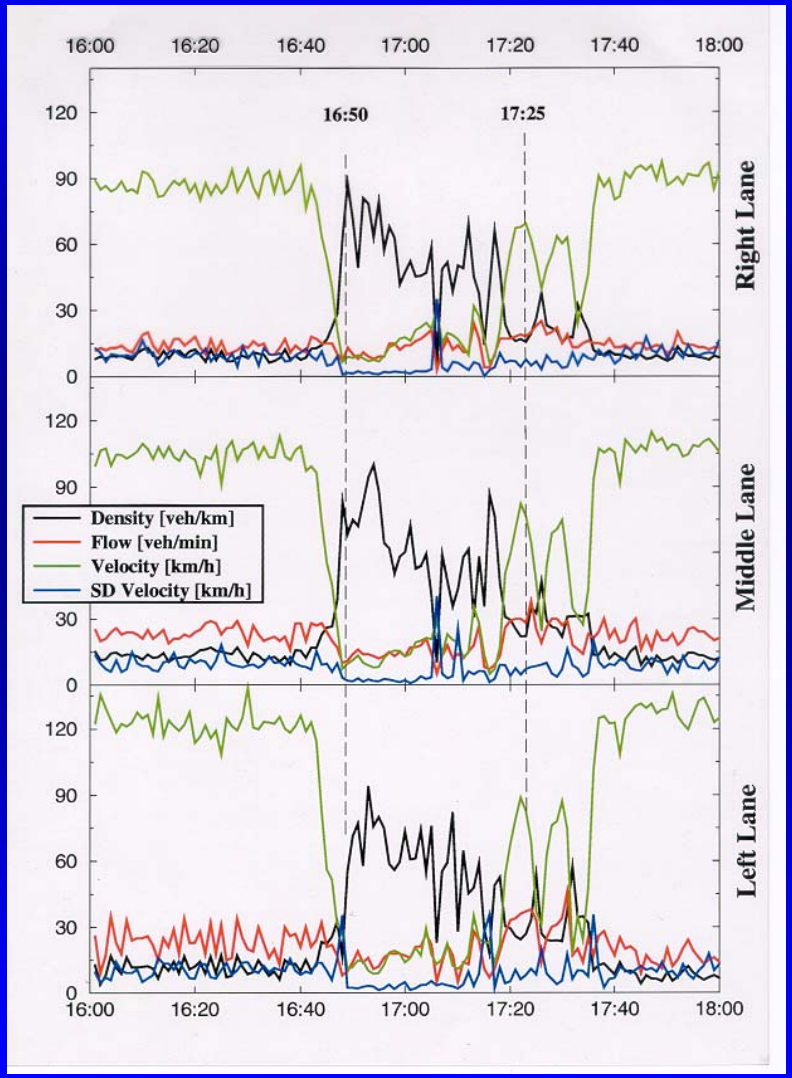
20020915 85 8 1 91 86 73 1 13 91
20020915 86 7 4 102 93 83 2 9 96
20020915 87 10 0 96 0 59 1 11 100

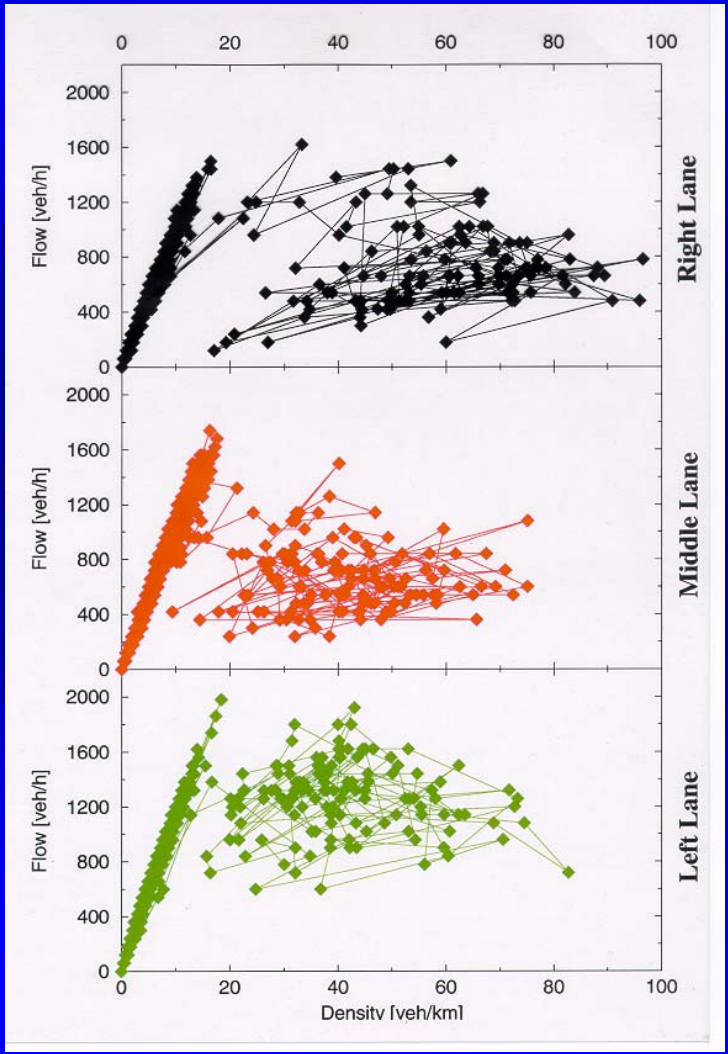
Density/Flow/Velocity



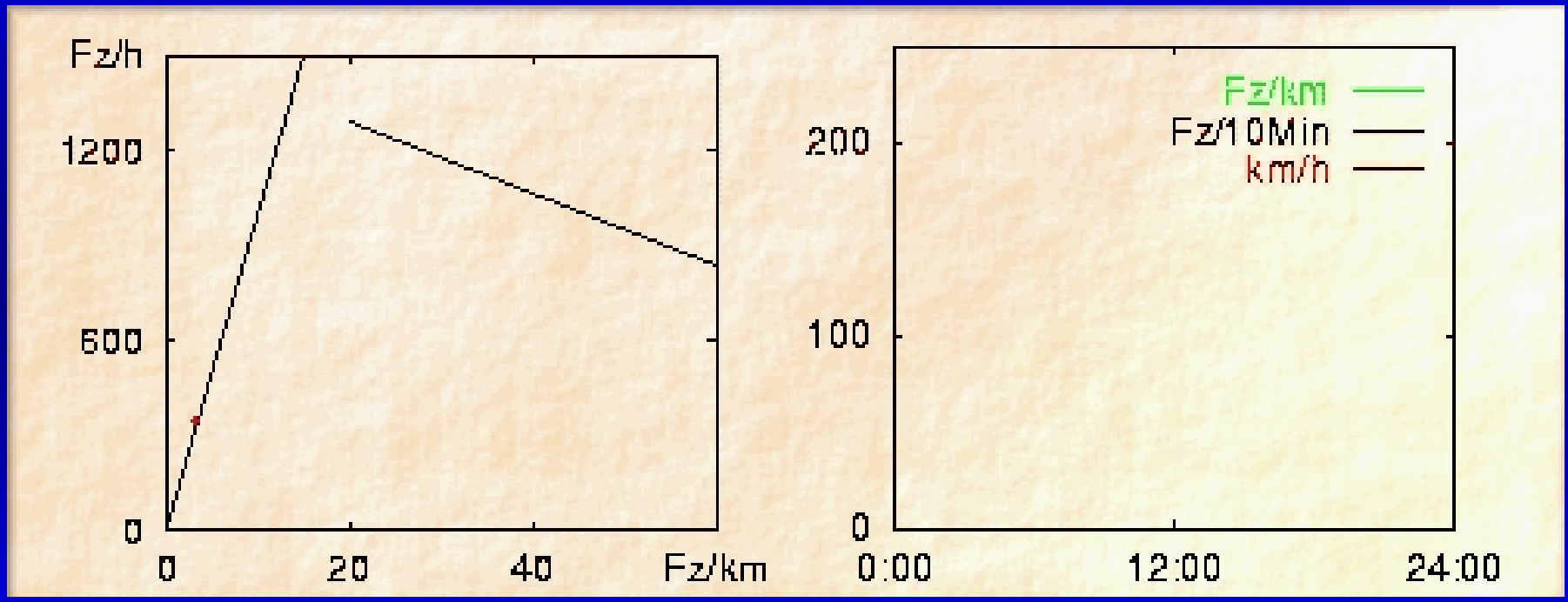
Lane Resolution and Traffic States



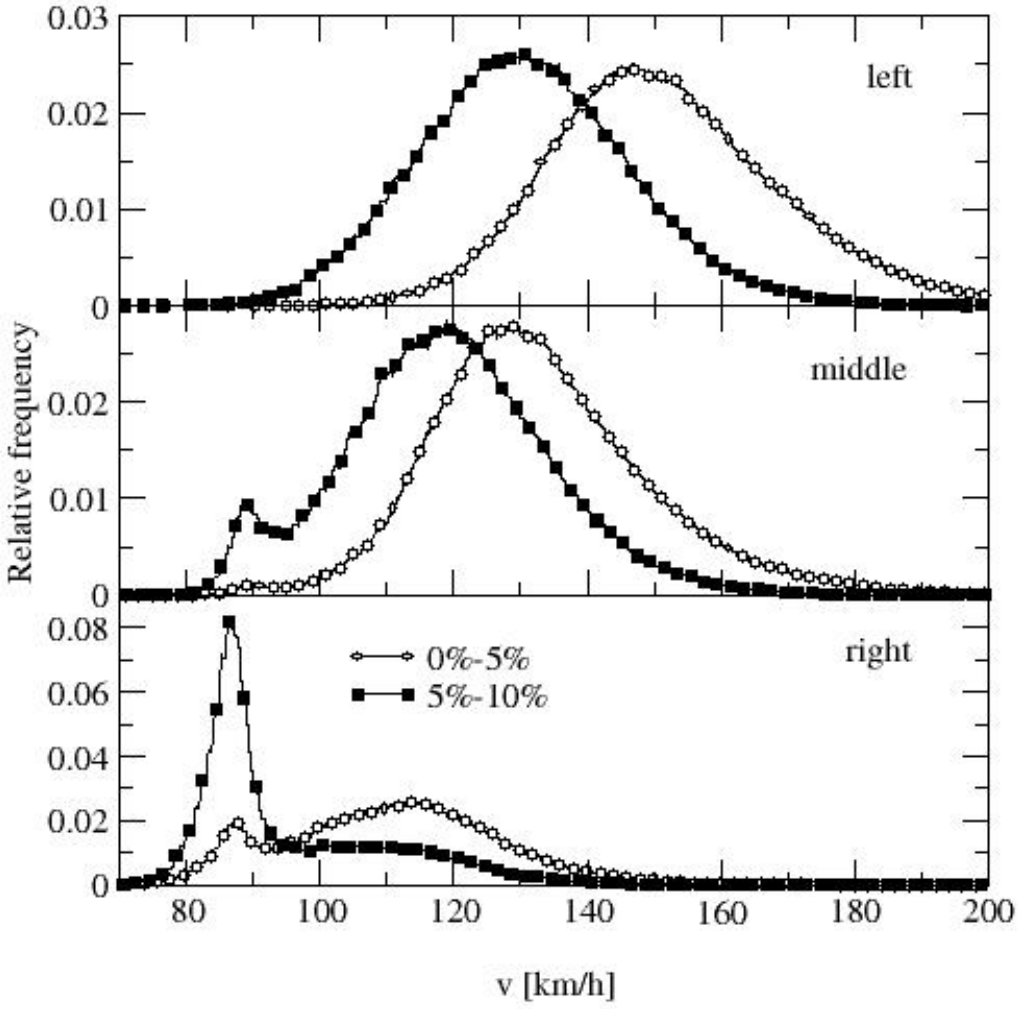
Fundamental Diagram



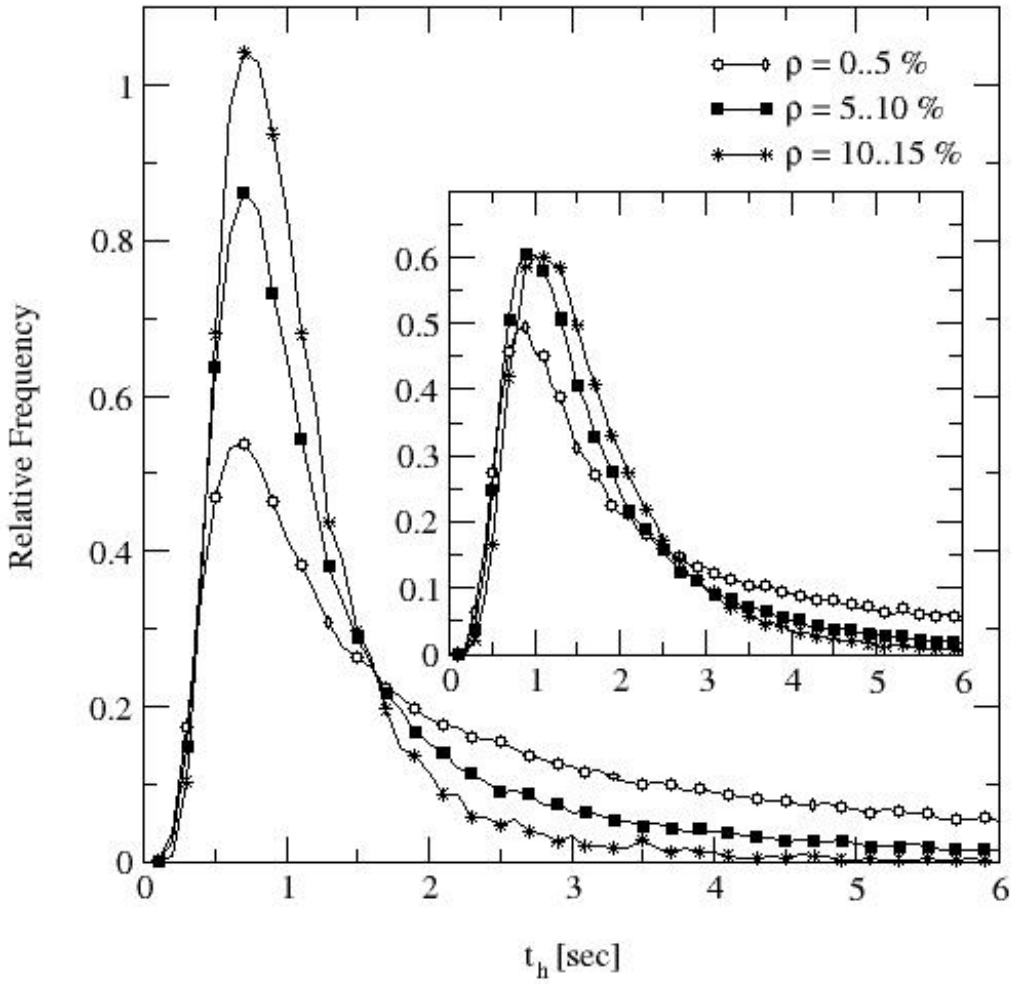
Dynamic Flow-Density Relation



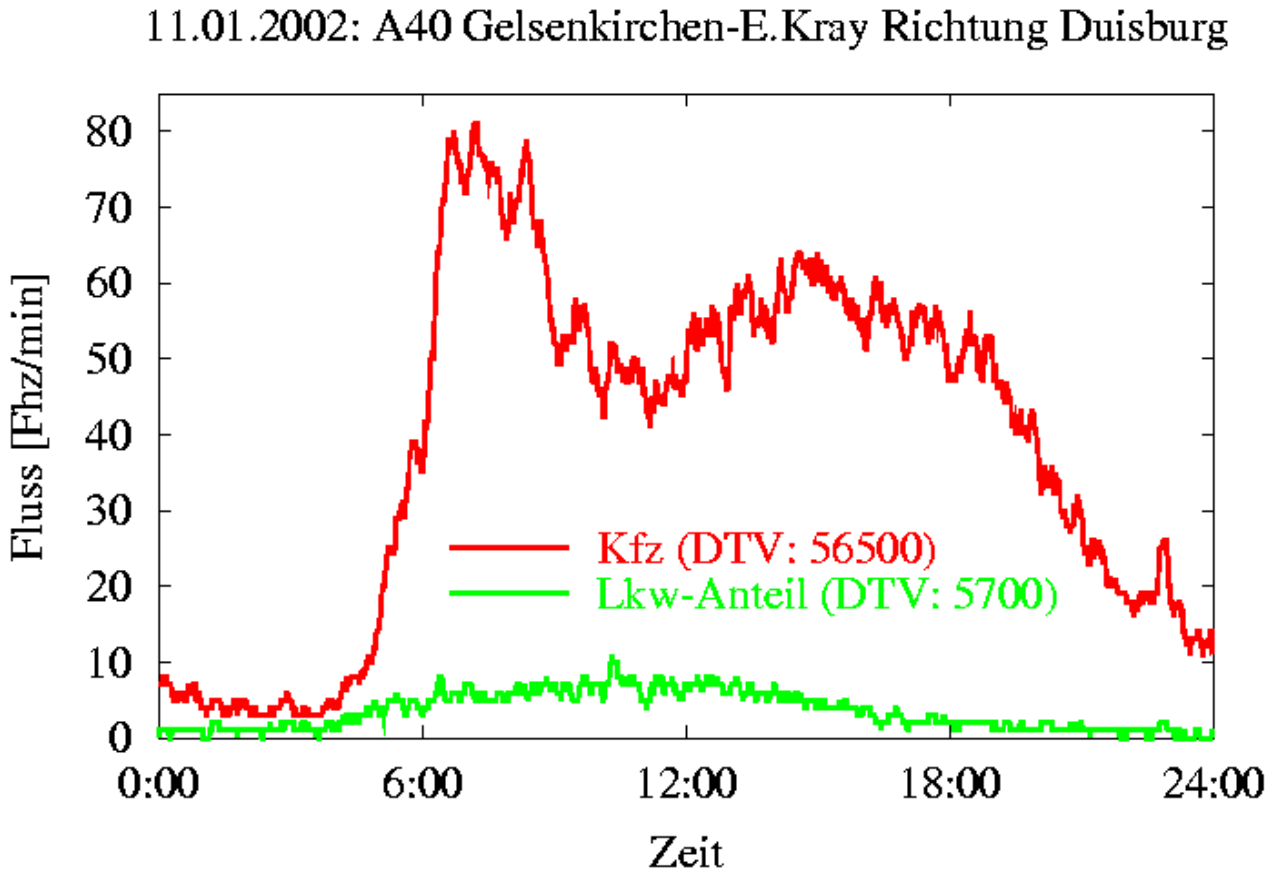
Speed Distribution



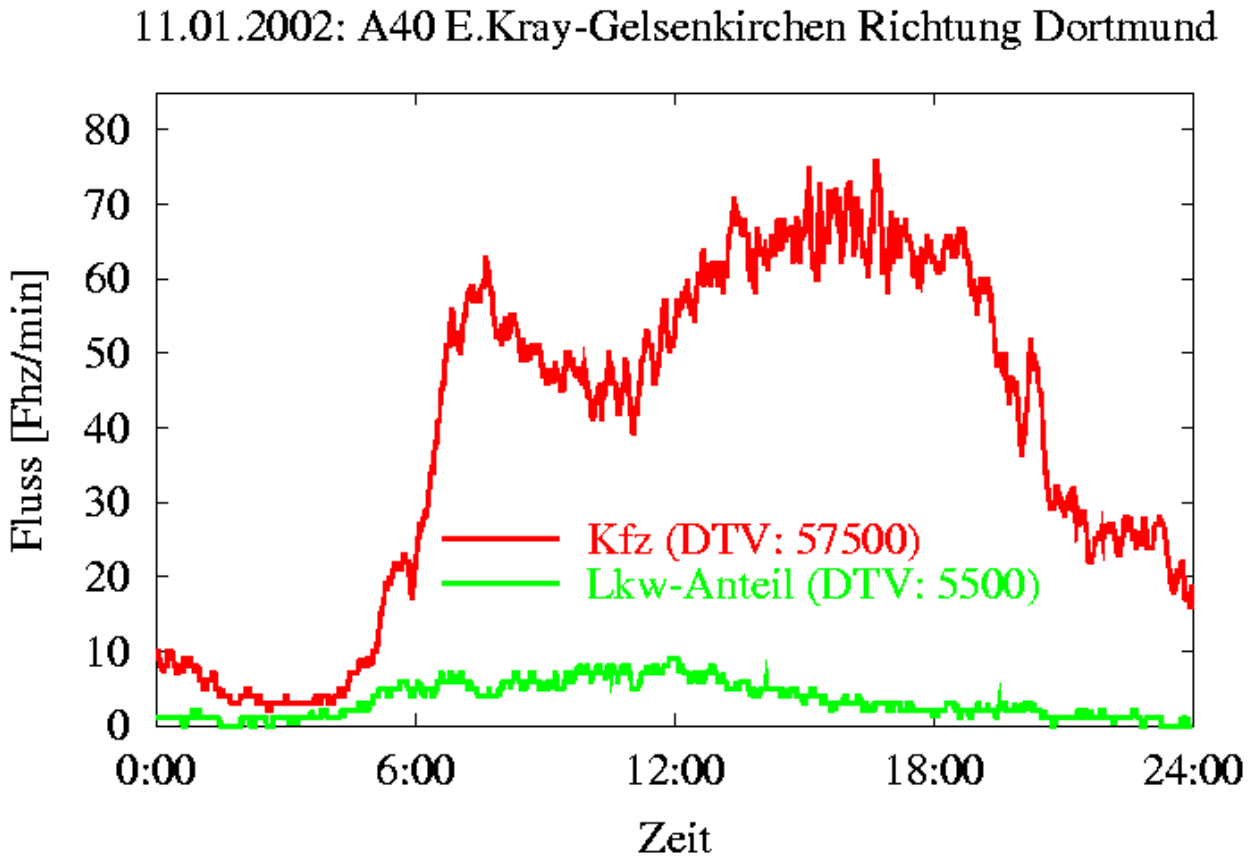
Time Headways



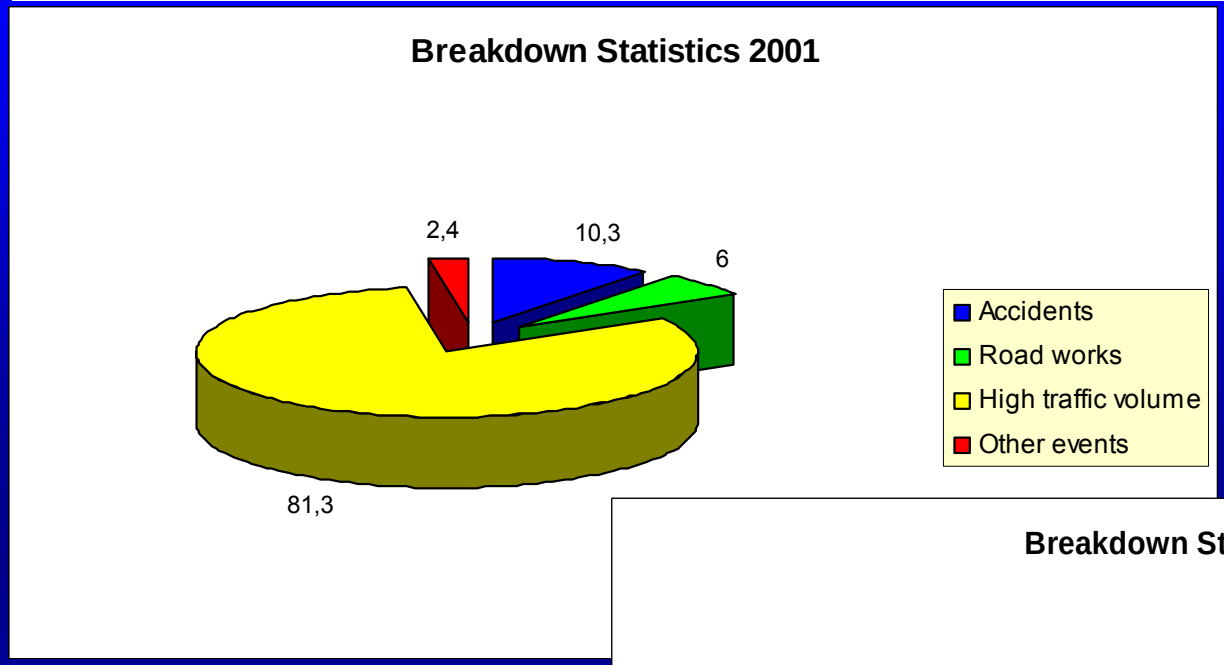
Daily Traffic Load BAB: West

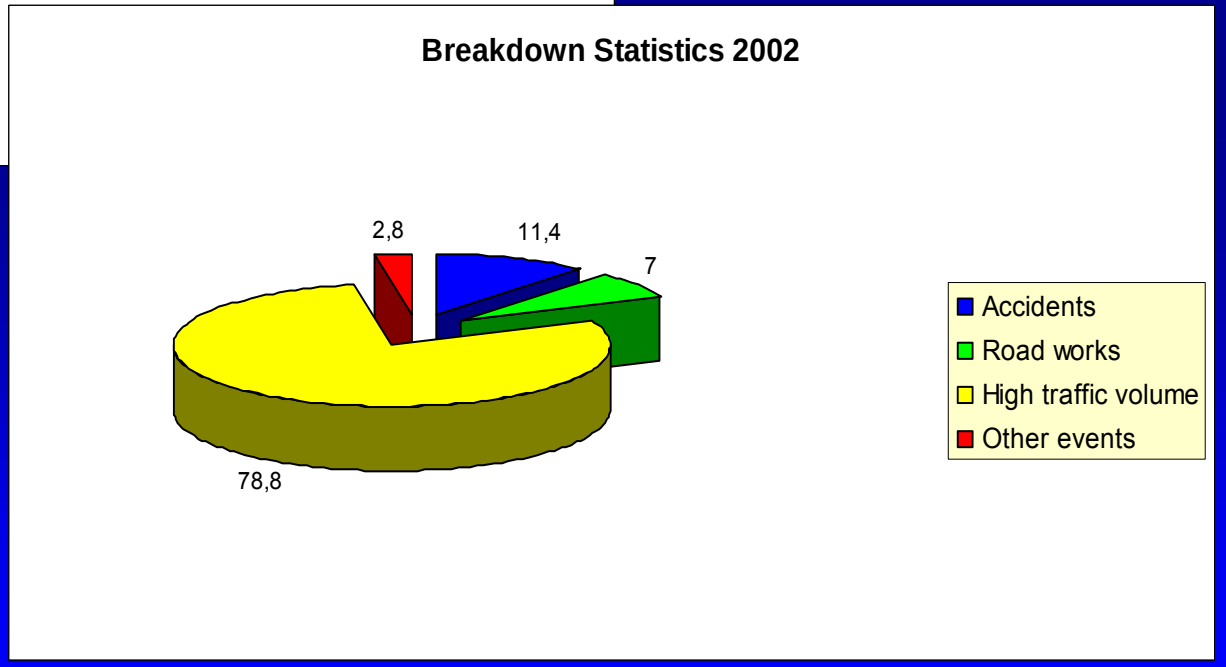


Daily Traffic Load BAB: East



Jam Statistics





General Strategy of Online-Simulations

- One-to-one (car by car) mapping of real traffic into the computer (via connection to detection devices, e.g. loops)
- Install a historical data base for evaluation and "background"
- Use a highly realistic but efficient microscopic simulation model ("Cellular Automaton", CA)
- Run the simulation and analyze the results: (e.g. actual flow pattern)
- Derive indirect quantities: travel times are measured by "virtual" floating cars
- Accelerate the simulation for a traffic forecast (again comparison with the historical data base)
- Formulate traffic informations
- Include driver reactions on the information and iterate

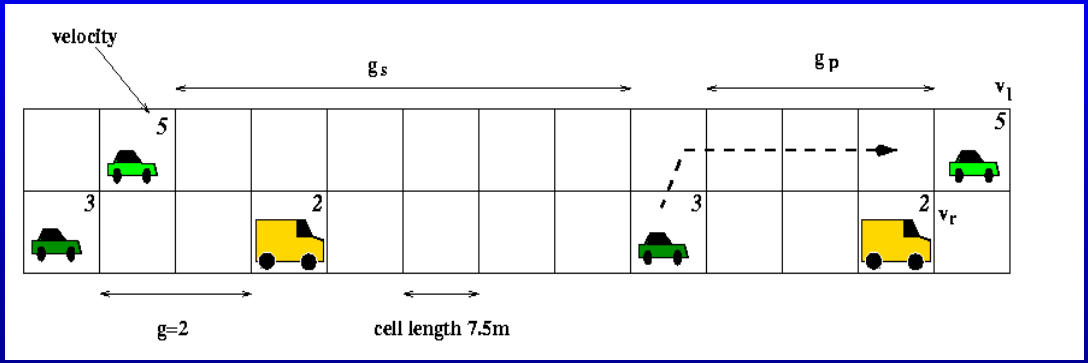
Modelling Traffic Flow

- Macroscopic models:
  - Traffic is similar to fluids
  - Continuity equation
  - Describe density waves
  - But: Assumption for function j(ρ)

$$\frac{\partial}{\partial t}\rho + \nabla \vec{j} = 0$$

- Microscopic models:
  - Traffic is similar to granular media
  - Describe car-following (interaction)

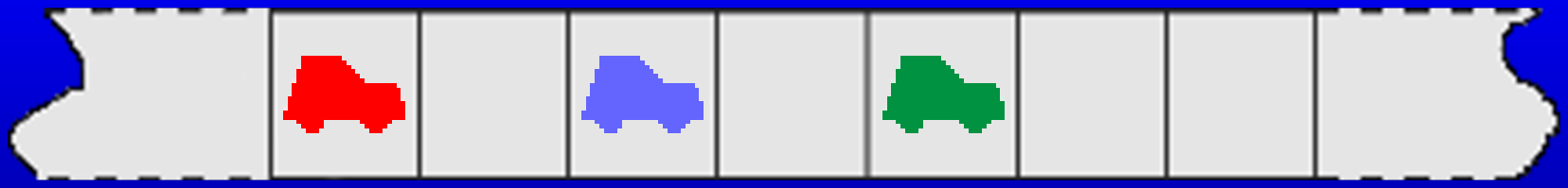
General Strategy



Cellular Automaton (CA) Model:

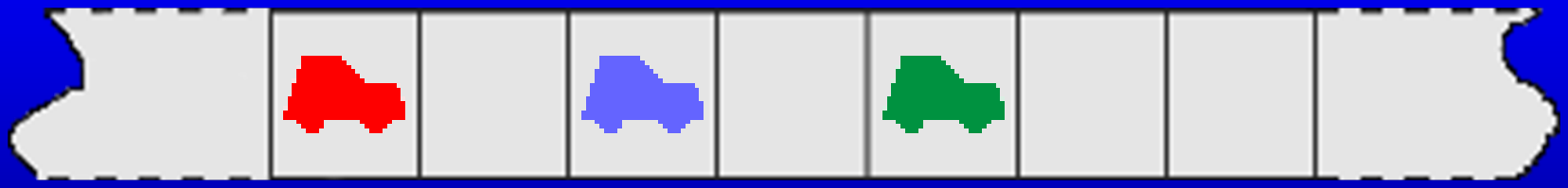
- Discrete in time and space
- Dynamics through update rules (in parallel)
- Fast and efficient algorithms
- Analysis of dynamical phases:
  free, synchronized and wide moving jams

Discrete Simulation Model



- Cell length = 7,5 m
- v = speed
- gap = # of empty cells between the cars

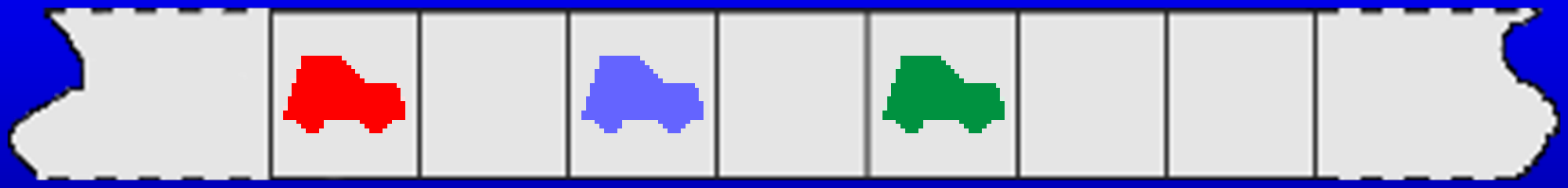
Cellular Automaton (I)



v = 2 v = 1 v = 2

- acceleration: $v \leftarrow \min(v + 1, v_{max})$

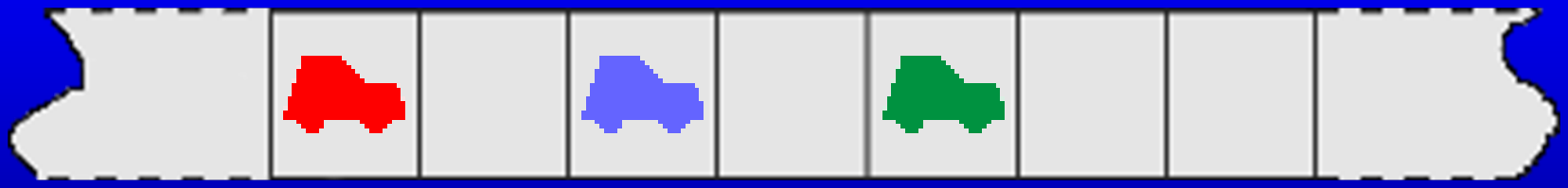
Cellular Automaton (II)



v = 1 v = 1 v = 2

- acceleration: $v \leftarrow \min(v + 1, v_{max})$
- braking: $v \leftarrow \min(v, gap)$

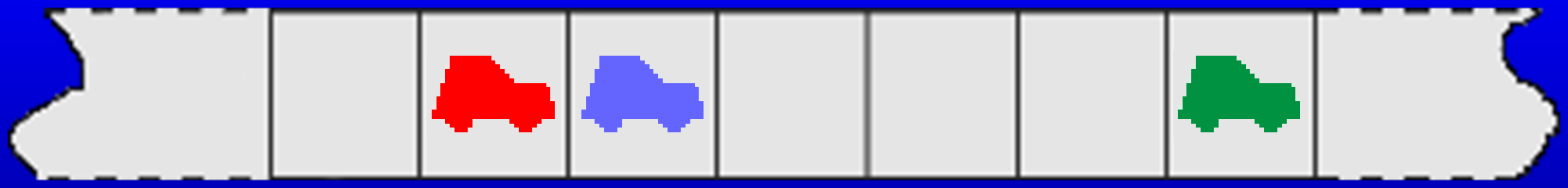
Cellular Automaton (III)



v = 1 v = 0 v = 2

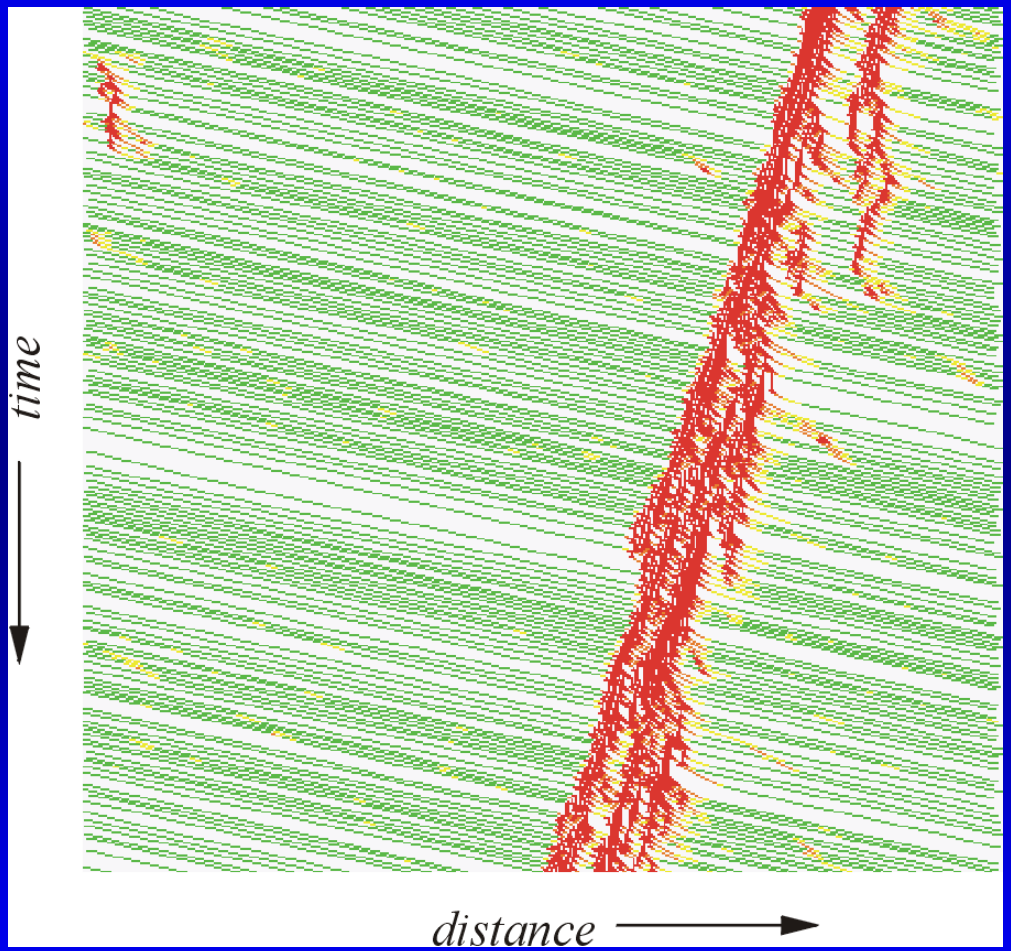
- acceleration: $v \leftarrow \min(v + 1, v_{max})$
- braking: $v \leftarrow \min(v, gap)$
- randomization with prob p_{dec}:
  $v \leftarrow \max(v - 1, 0)$

Cellular Automaton (IV)

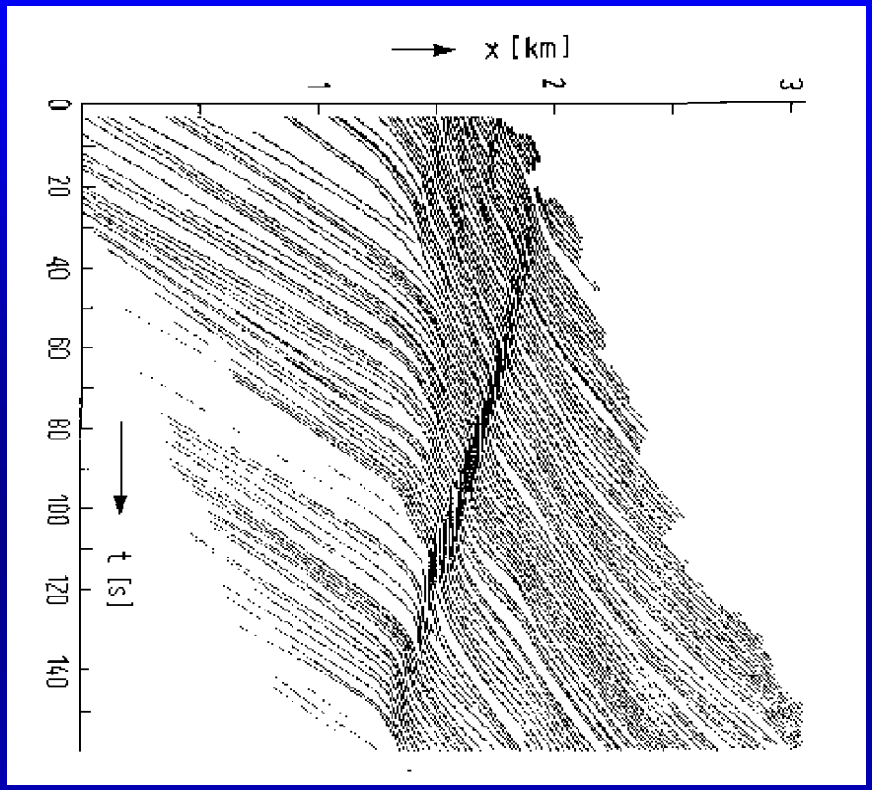


- acceleration: $v \leftarrow \min(v + 1, v_{max})$
- braking: $v \leftarrow \min(v, gap)$
- randomization with prob p_{dec}:
  $v \leftarrow \max(v - 1, 0)$
- driving: $x \leftarrow x + v$

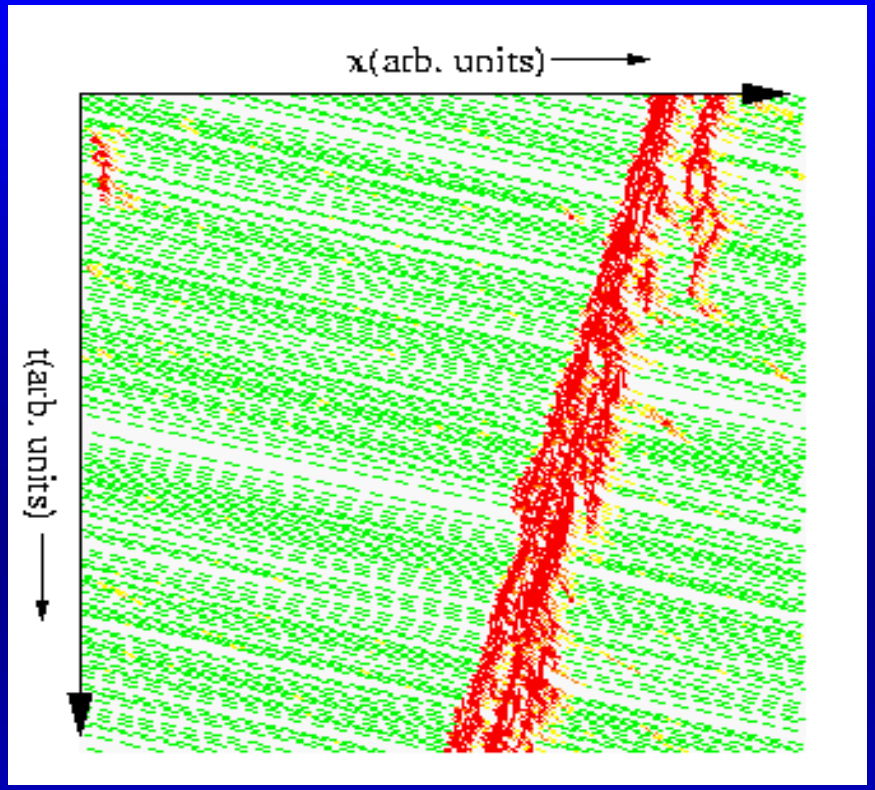
Simulated Jams



Jam Formation

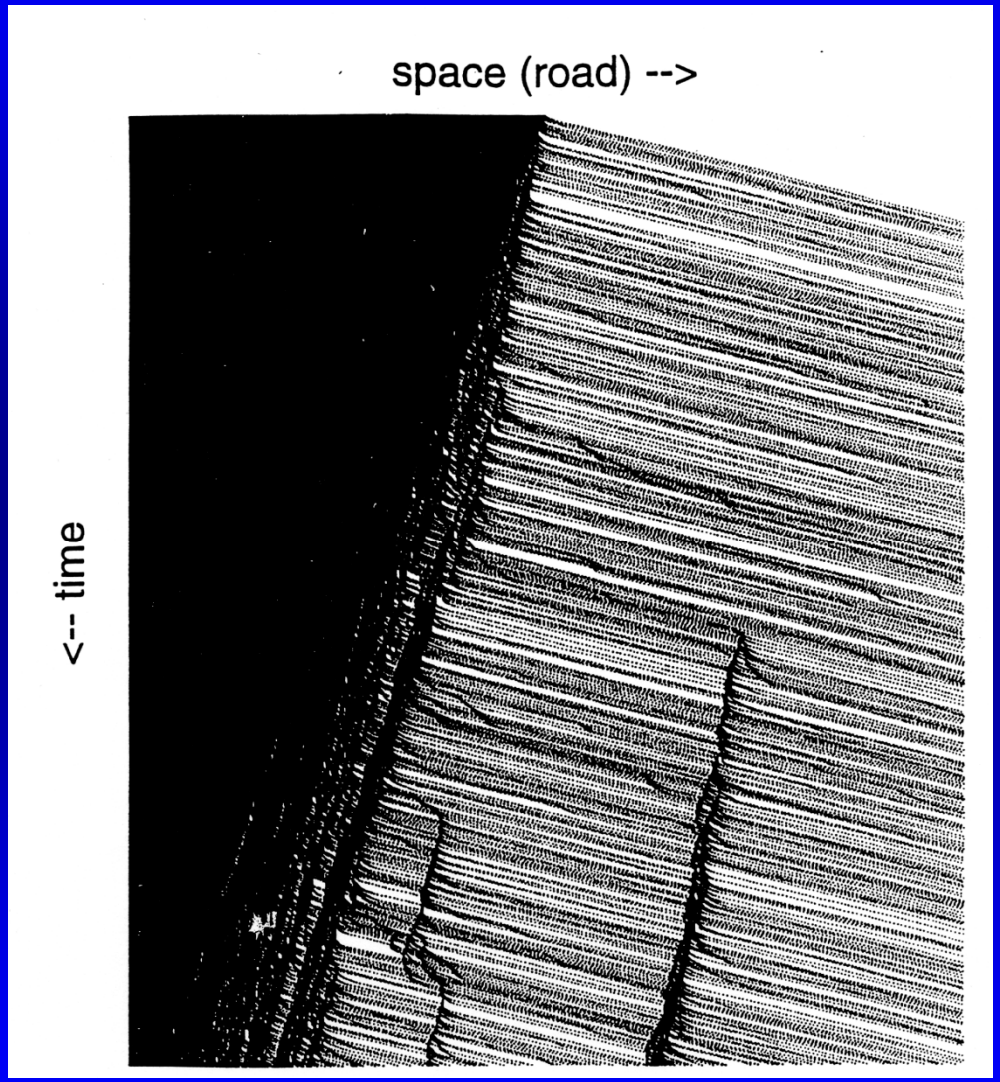


Air video analysis
(Treiterer 1965)



Simulation

Outflow from a Megajam: SOC

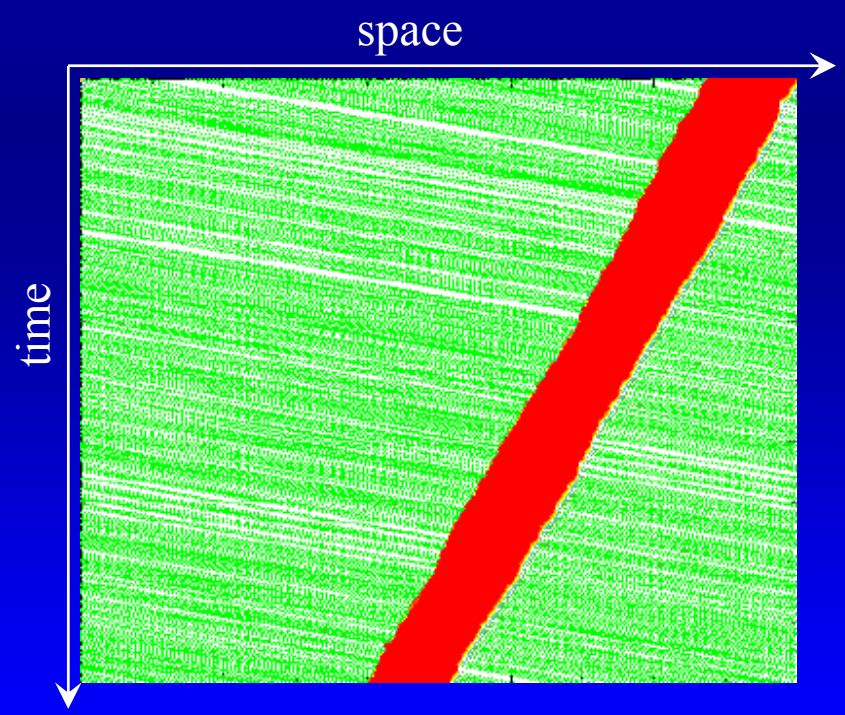


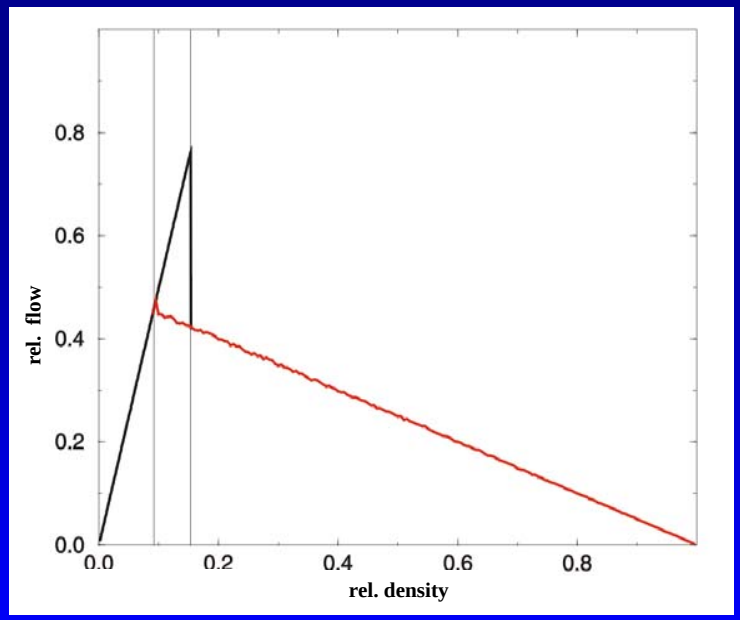
Velocity Dependent Randomization

$$p_{dec} = p_{dec}(v)$$

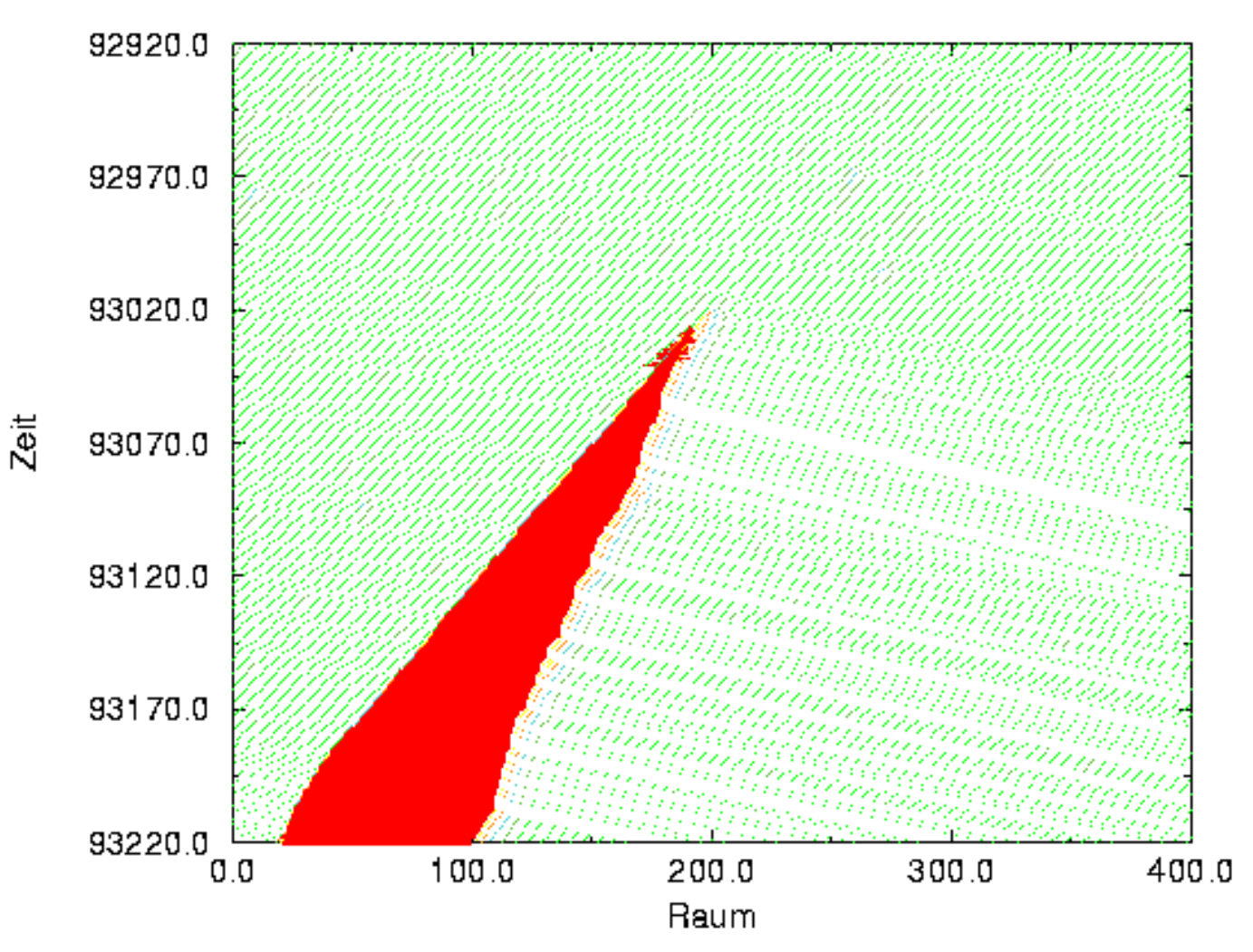
$$p_{dec} = \begin{cases} p_0 & \text{,for } v = 0 \\ p & \text{,else} \end{cases}$$

with: $p_0 > p$

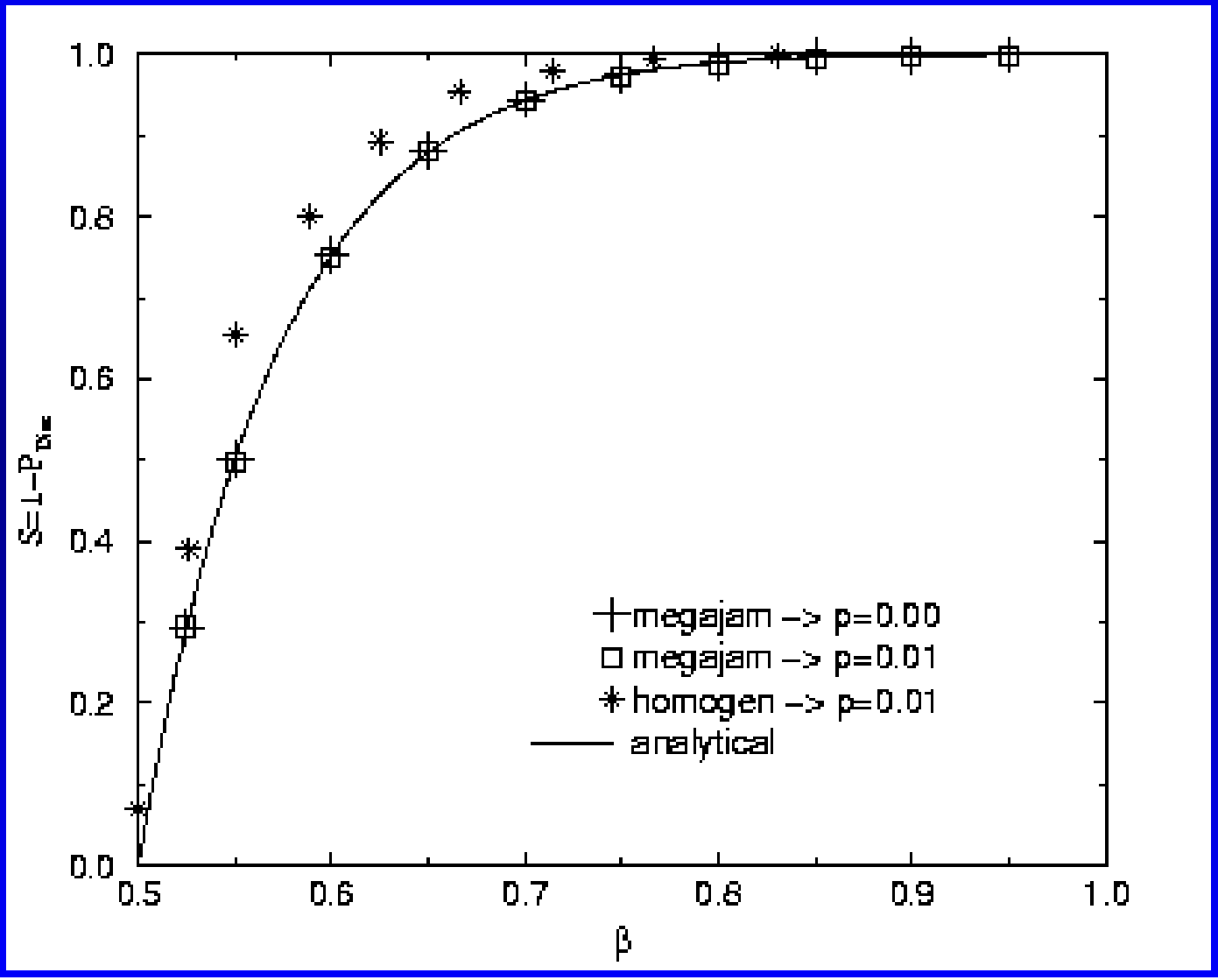




Metastability



Jam Probability



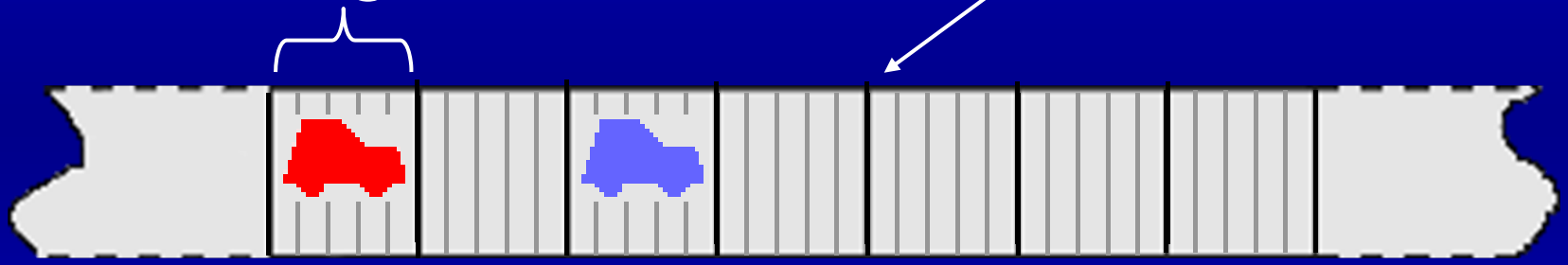
Anticipation

Anticipation: take into account the speed of the vehicle ahead

Effective distance: $gap_{eff} = gap + v_{pred}$

Vehicle length: 5 cells

1,5 m



$v = 1 + 4$ $v = 5$

- small time headways
- very high flux
- realistic lane changes

Model Extensions

Requirements:

- Unaffected driving in free traffic
- Reaction on acceleration or braking
- Delayed acceleration out of jams (capacity drop)

Ansatz:

- Velocity dependent reaction (VDR)
- Anticipation of driver's behavior
- Adjustment of the cell length

Driver-Behaviour-Modell (Lee et al)

Defensive

Optimistic

$$\tau_l(v_{n+1}) = v_{n+1}/D \qquad \tau_f(v_n^*) = v_n^*/D$$

$$\Delta_n = l + \underbrace{\max\left\{0, \min\left\{g_{add}, v_n - g_{add}\right\}\right\}}_{0,1,2,3,g_{add}=4}$$

$$v_n \le v_{n+1} \le v_{n+2} \vee v_{n+2} \ge v_{max} - 1$$

$$\tau_f(v_n^*) = \underbrace{\max\left\{0, \min\left\{v_n^*/D, t_{Safe}\right\} - 1\right\}}_{t_{Safe}-1=2,1,0}$$

$$\tau_l(v_{n+1}) = \underbrace{\min\left\{v_{n+1}/D, t_{Safe}\right\}}_{t_{Safe}=3,2,1,0}$$

$$\Delta_n = l$$

$$v_n^* \le \left\langle \frac{\left[x_{n+1} - x_n - \Delta_n\right] + v_{n+1}\left[\tau_l - \frac{D}{2}(\tau_l^2 + \tau_l)\right]}{v_n^*\left[\tau_f - \frac{D}{2}(\tau_f^2 + \tau_f)\right]} \right\rangle$$

- **Determination of the stochastic parameter**

  $p \rightarrow \max\{p_d, p_0 - v_n(p_0 - p_d)/v_{slow}\}$

- **Determination of the safe velocity**

  $\max(v_n^*)$

- **Acceleration**

  $v_n \rightarrow \min\{v_{max}, v_n + a, \max\{0, v_n - D, \max(v_n^*)\}\}$

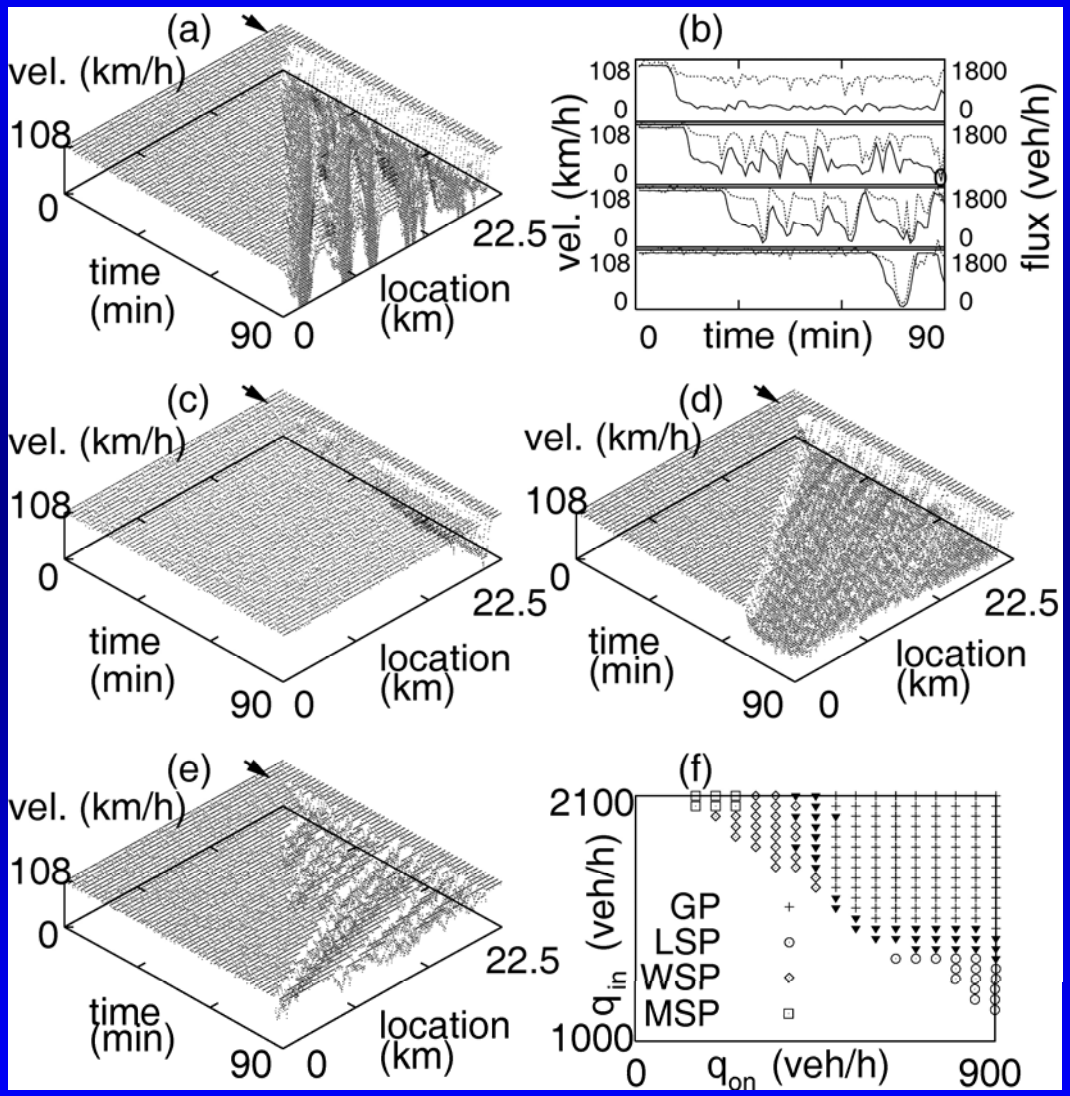
- **Deceleration**

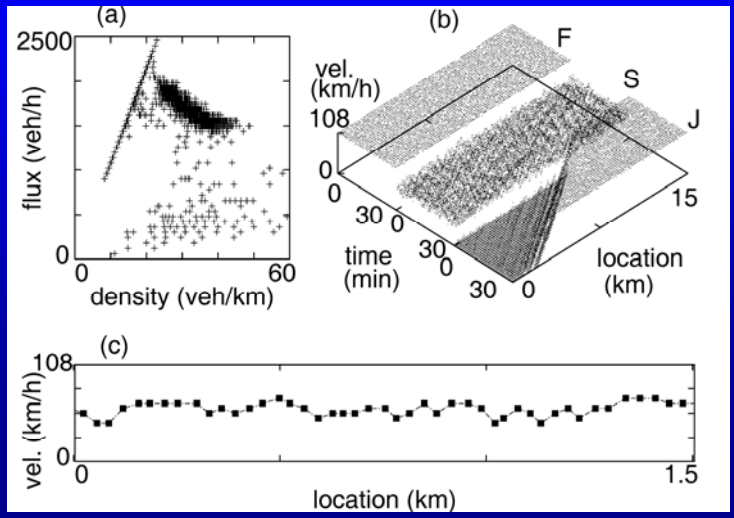
  $v_n \rightarrow \max\{0, v_n - D, v_n - 1 \text{ with probability } p, \max(v_n^*)\}$

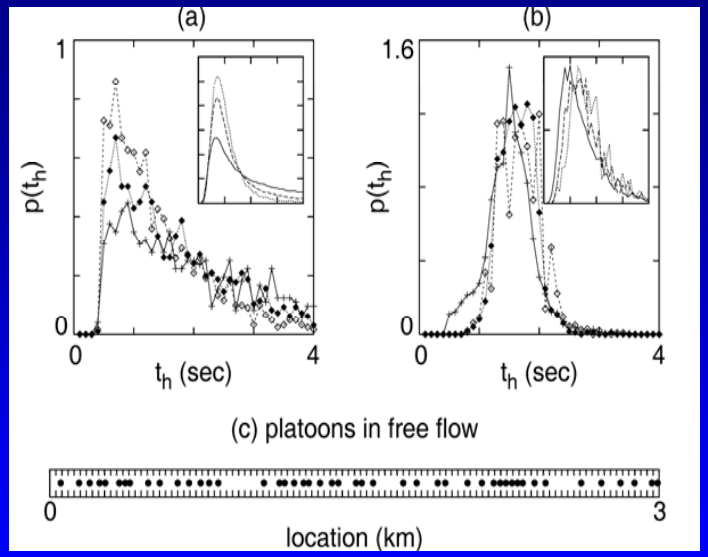
- **Movement**

  $x_n \rightarrow x_n + v_n$

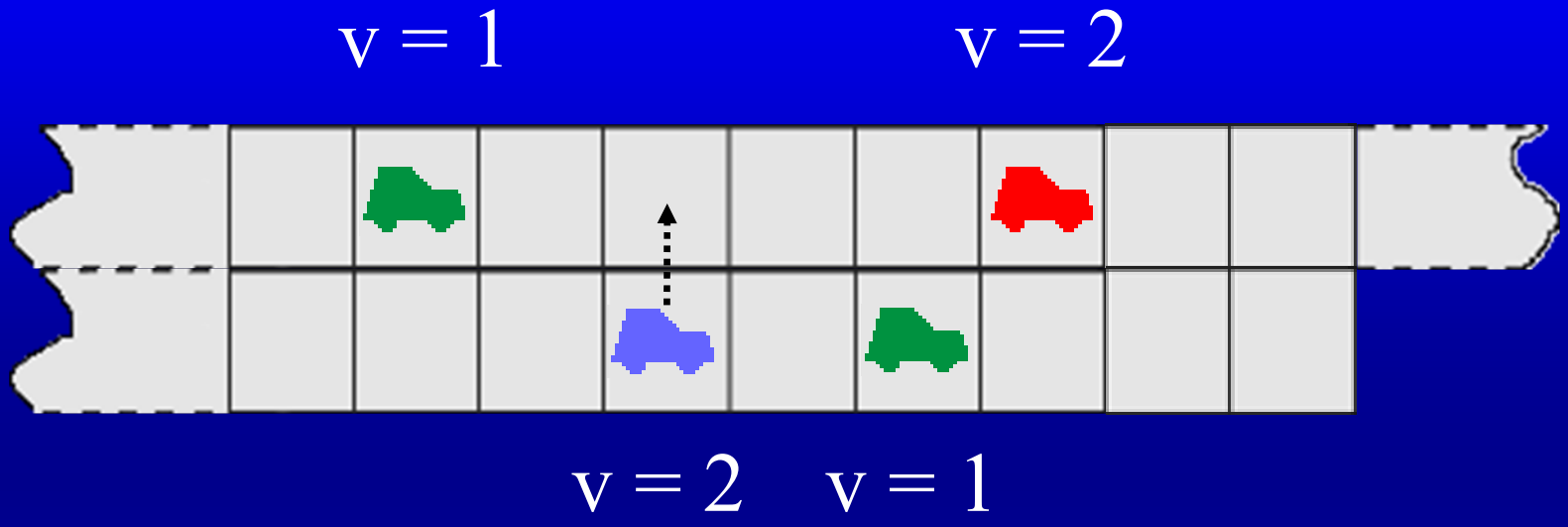
Traffic Phases







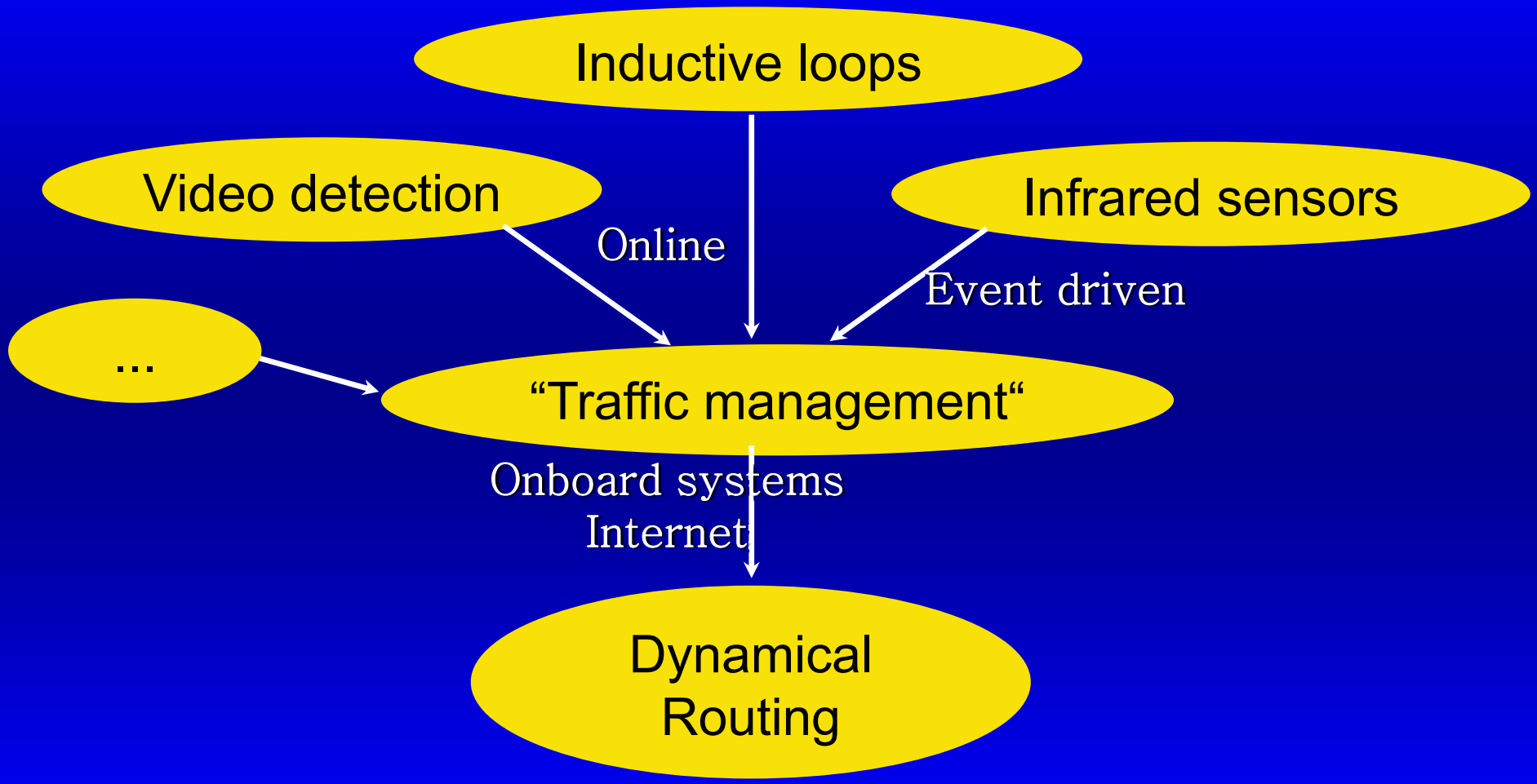
Lane Changing



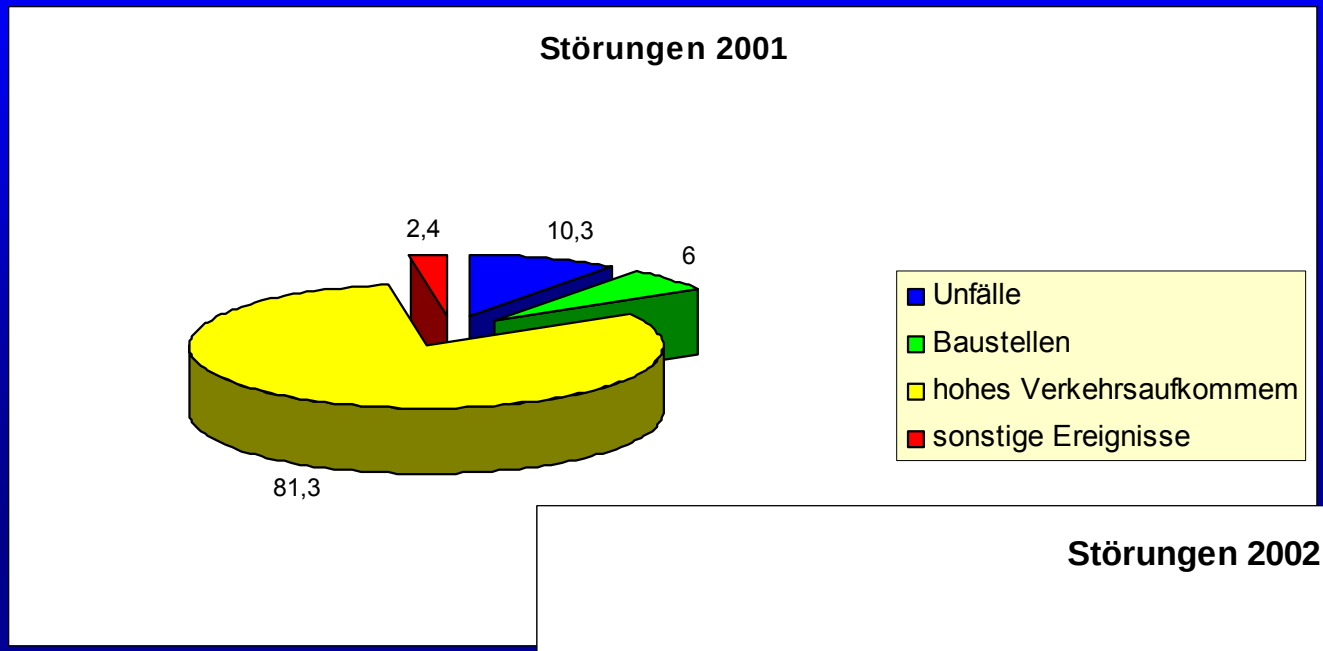
Lane change if

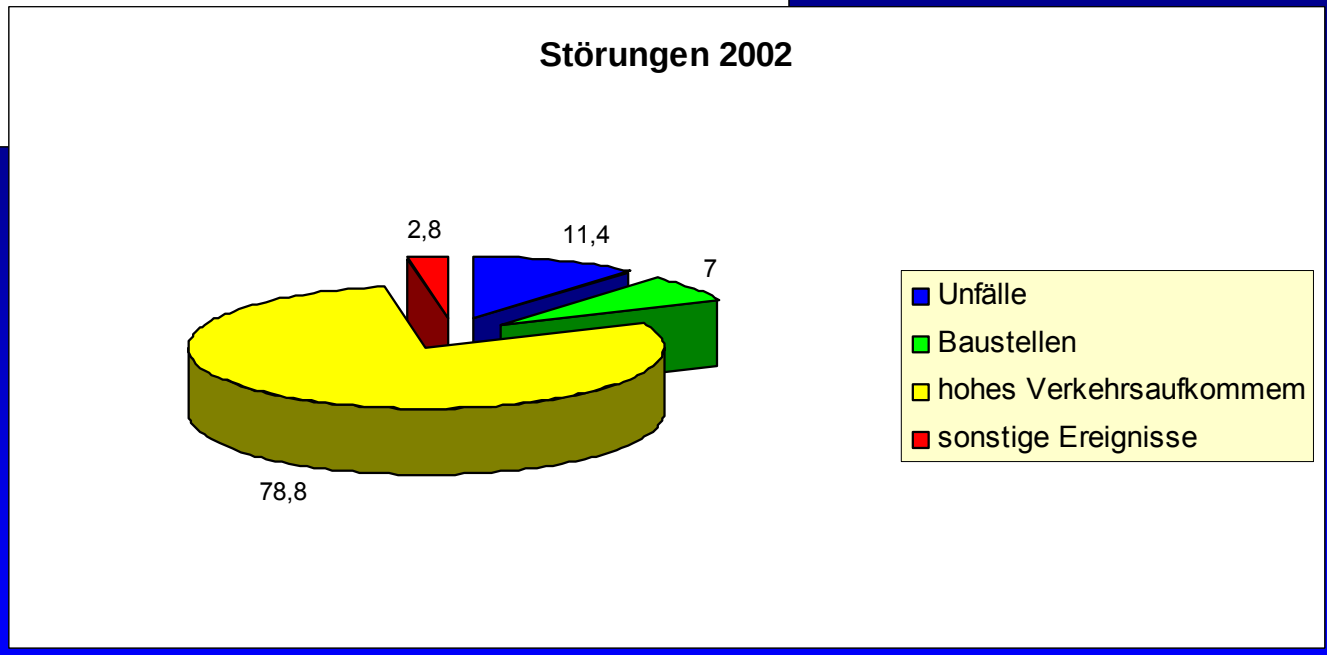
1. the driver wishes it,
2. it is allowed
3. headways remain ‘safe‘ .

Informations in Transport Systems

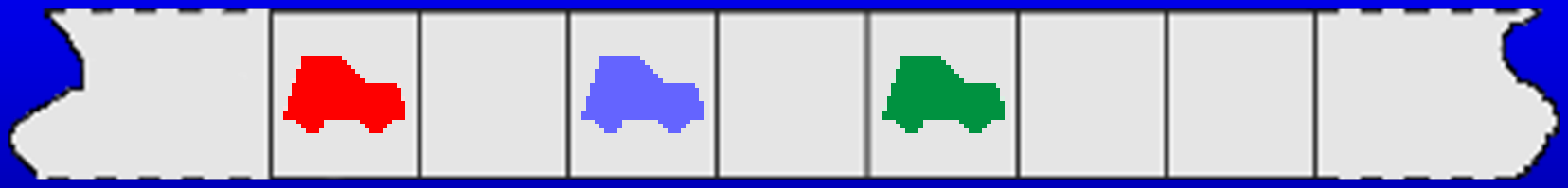


Jam Statistics



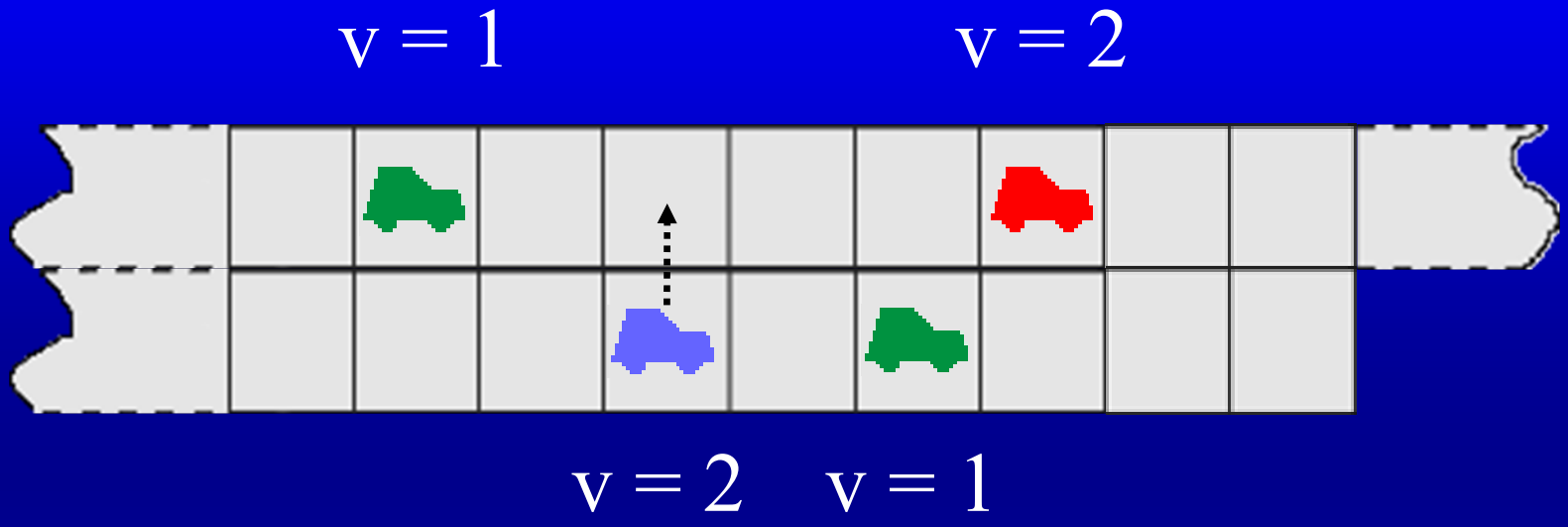


Efficient discrete Simulation Modell



- Cell length = 7,5 m
- v = speed
- gap = number of empty cells between the cars

Lane Changing



Lane changing if

1. it is desired,
2. it is legal and
3. Safety distance is obeyed.

Lane-Changing Rules

$t_h = gap/v$
$t_s = \min(v,6)$
$gap_{eff} = gap + \max(v_{anti}-7,0)$
$v_{anti} = \min(gap_{pred}, v_{pred})$

1. $b_n = 0$ und $b_{n+1} = 1$ und $t_h < t_s$
2. $gap_{eff} >= v$
3. $gap_{back} >= v_{back}$

Traffic Informations / Navigation

- Static navigation / maps
- Dynamic navigation (RDS-TMC/Private)
- Pre-trip: Internet / TV
- On-trip: radio / mobile phone / Internet / digital TV / information panels
- Post-trip: Internet

www.autobahn.nrw.de

Verkehrslage in NRW

Hochrechnung für Bundesautobahnen

Verkehrsinfo.NRW

- Erläuterungen
- Technische FAQ
- Impressum
- english version

Verkehrsinformationssystem autobahn.NRW

Mit den folgenden Links können Sie direkt auf die entsprechende Karte gelangen:

aktuelle Verkehrslage	Prognose 30 min	Prognose 60 min
NRW Übersicht	NRW Übersicht	NRW Übersicht
Aachen	Aachen	Aachen
Köln	Köln	Köln
Ruhrgebiet	Ruhrgebiet	Ruhrgebiet
Ruhrgebiet West	Ruhrgebiet West	Ruhrgebiet West
Ruhrgebiet Ost	Ruhrgebiet Ost	Ruhrgebiet Ost
Ostwestfalen	Ostwestfalen	Ostwestfalen
Münsterland	Münsterland	Münsterland
Sauerland	Sauerland	Sauerland
Bonn	Bonn	Bonn
Niederrhein	Niederrhein	Niederrhein

Ministerium für Verkehr, Energie und Landesplanung des Landes Nordrhein-Westfalen

Straßen.NRW. Landesbetrieb Straßenbau NRW

Physik von Transport und Verkehr

Dieses Projekt wurde von der europäischen Union finanziell unterstützt

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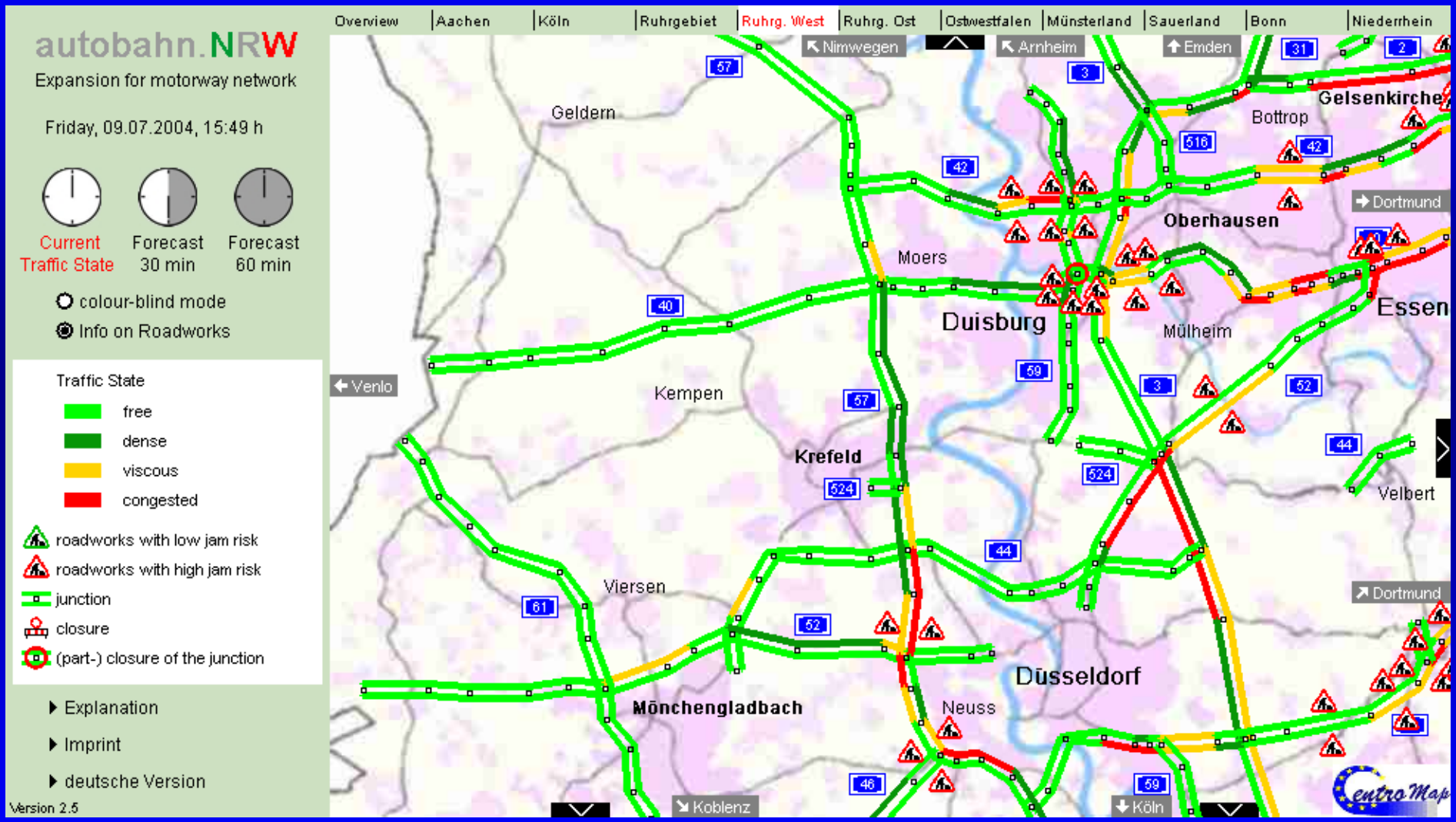
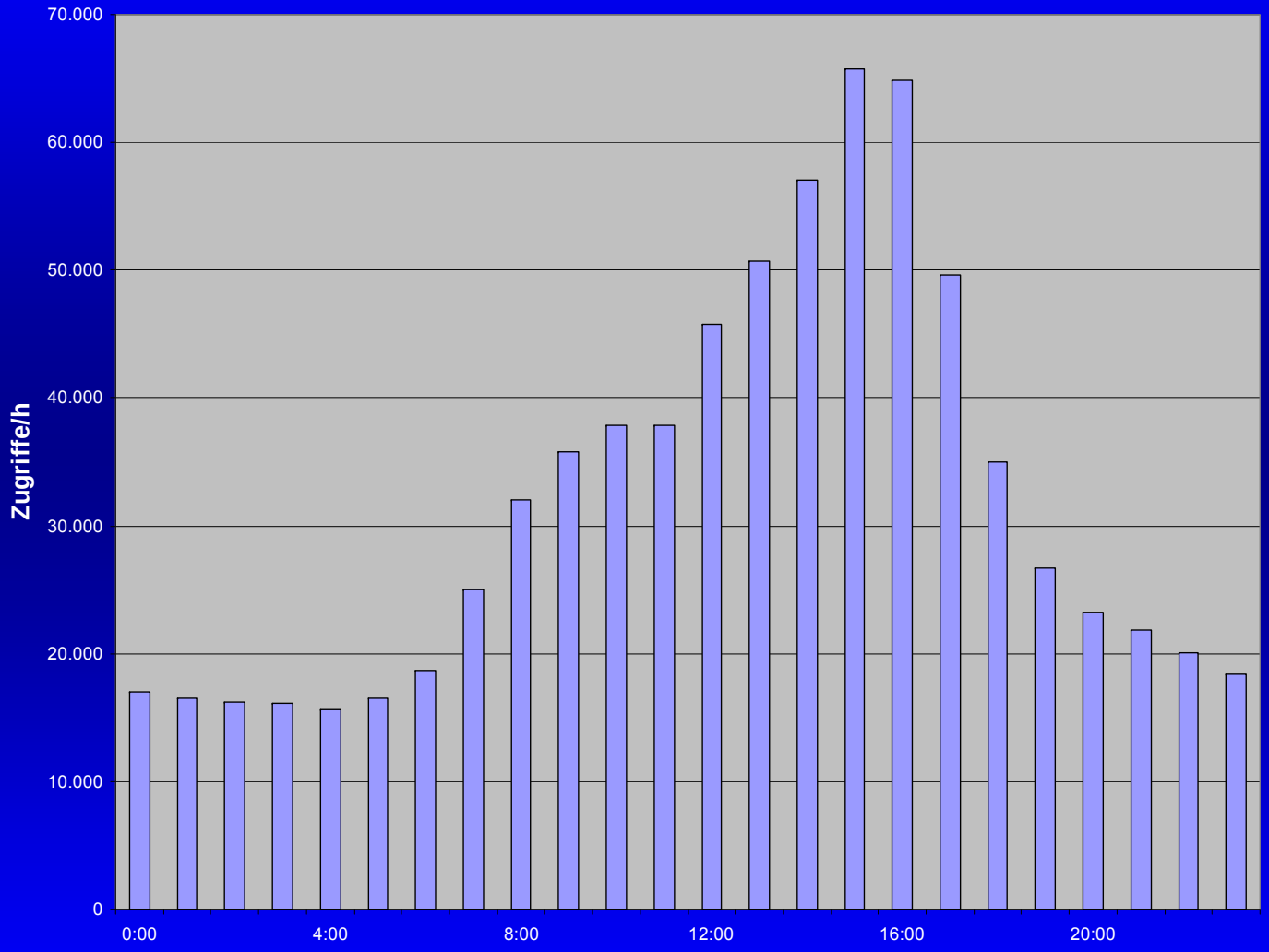
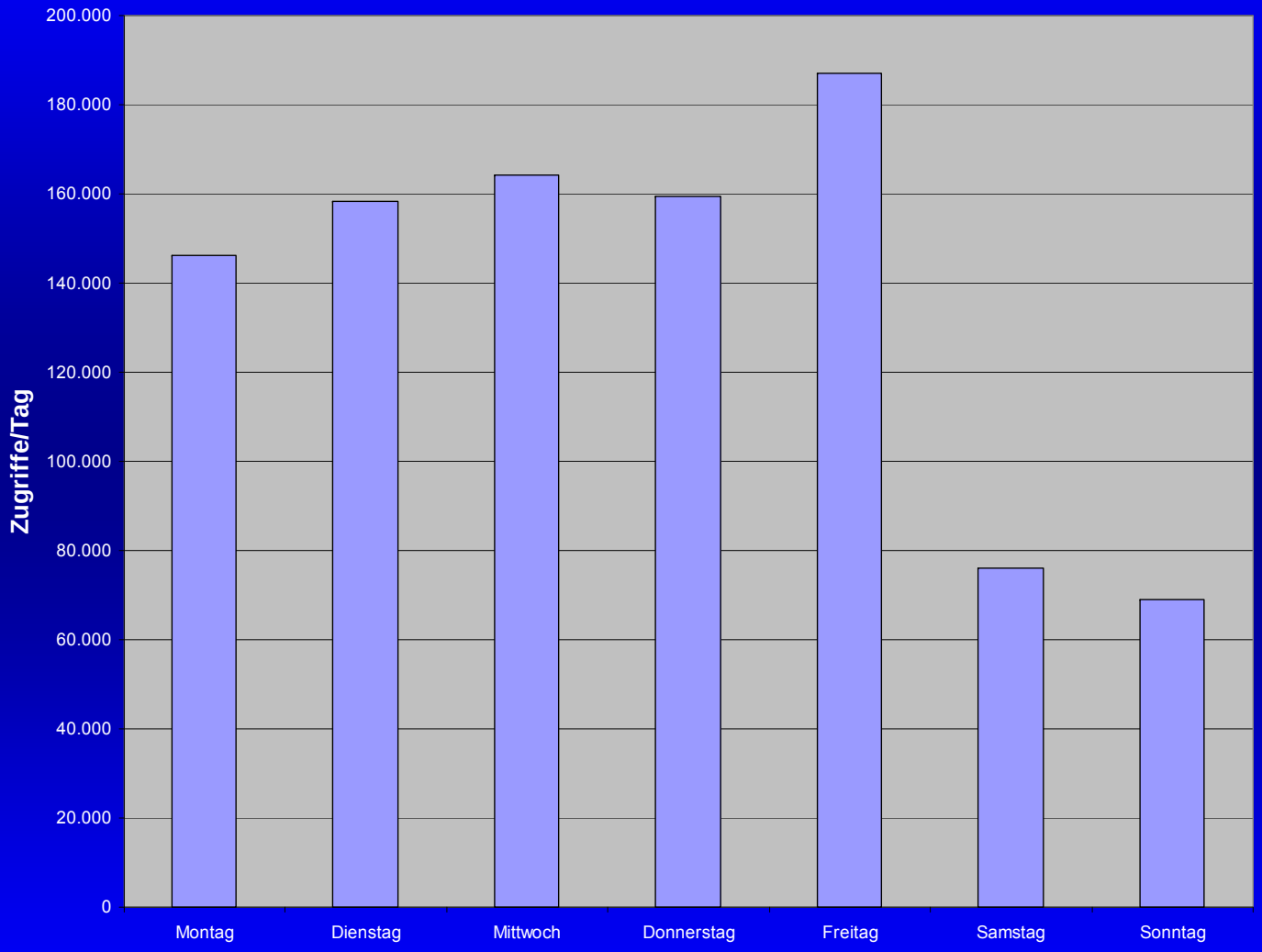


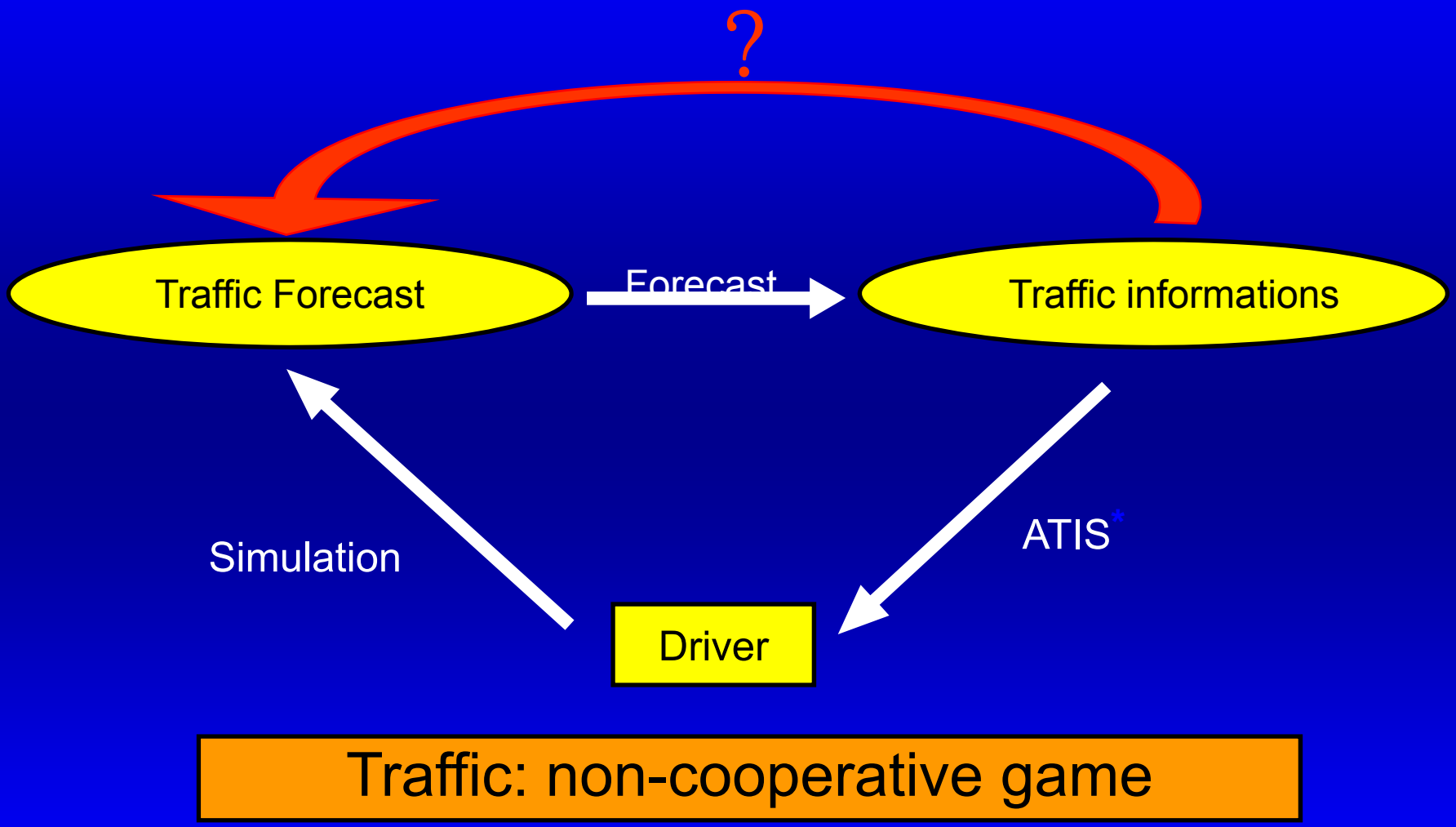
Users per Hour



Users per Week-Day

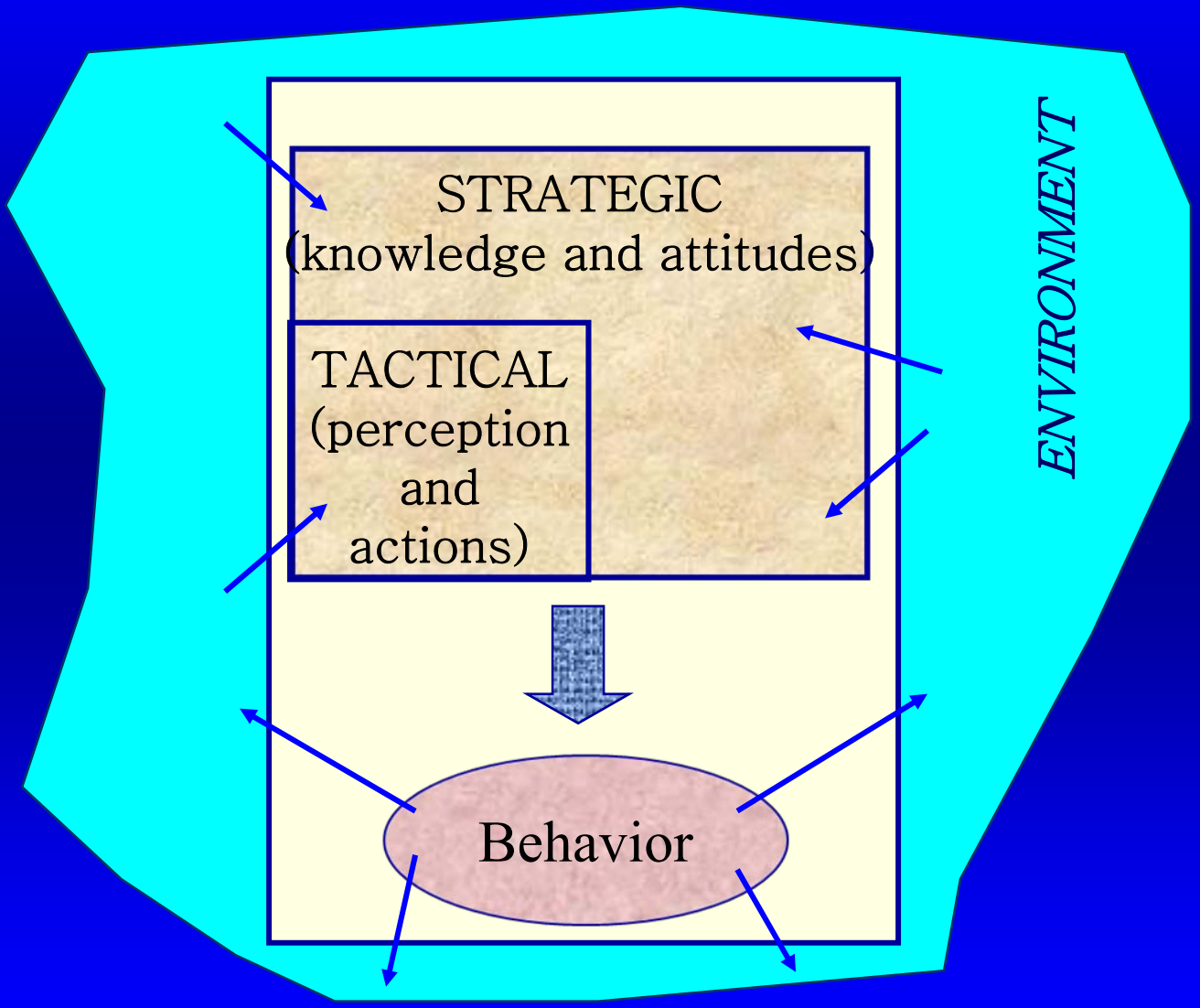


Anticipatory Traffic Forecast

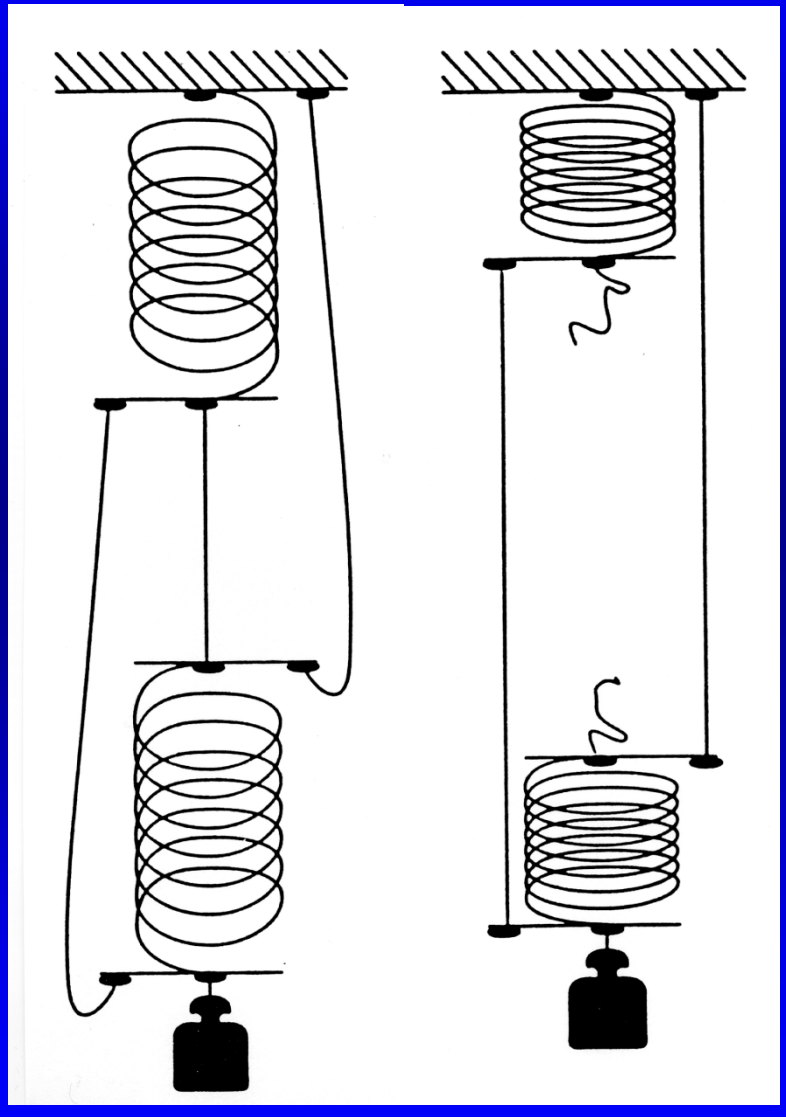


Traffic: non-cooperative game

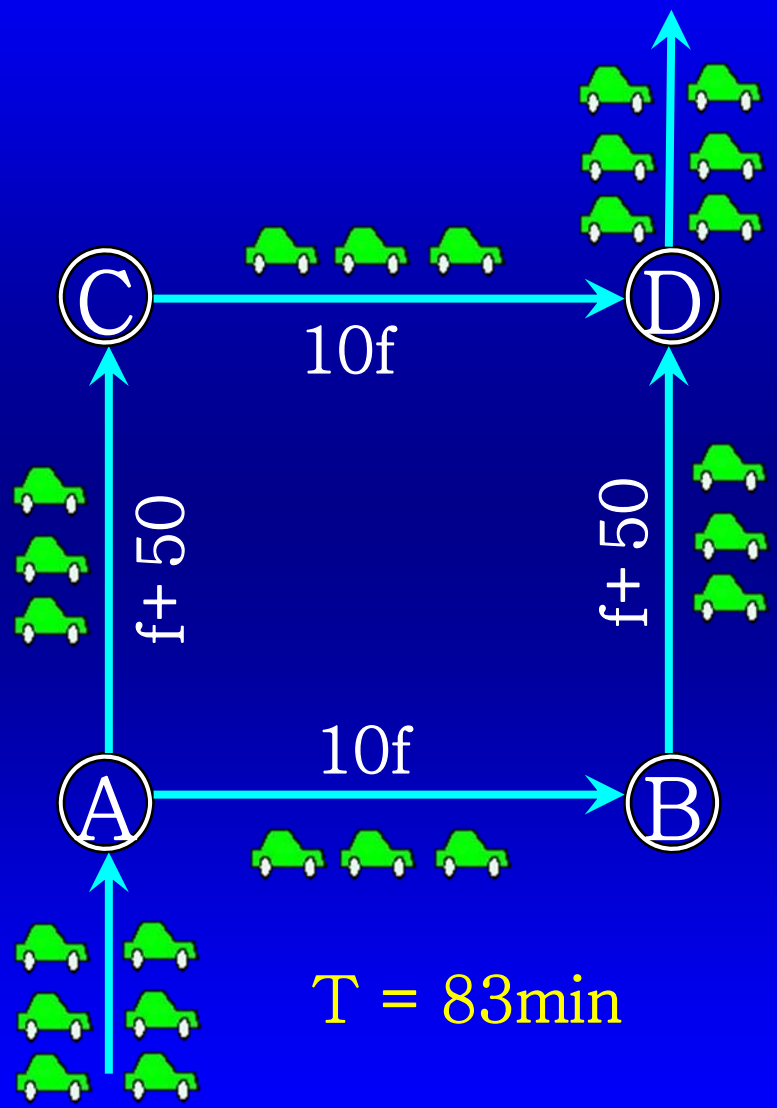
Multi-Agent Model

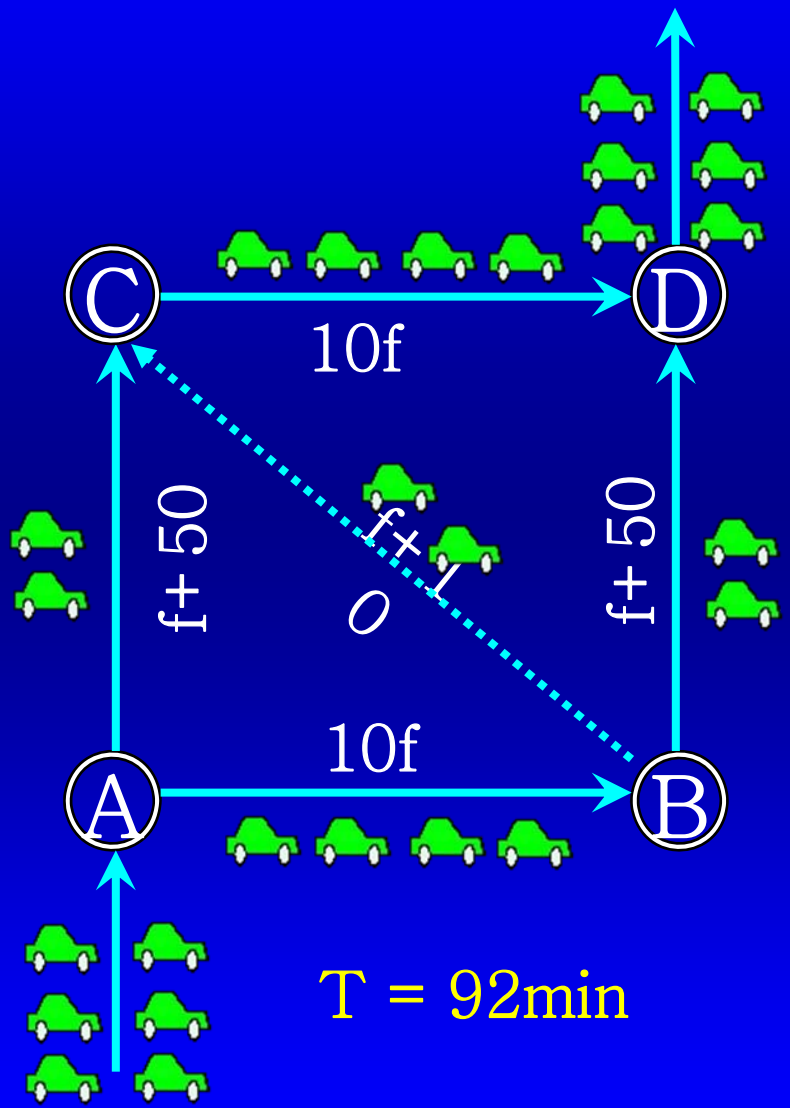


The Braess Paradox

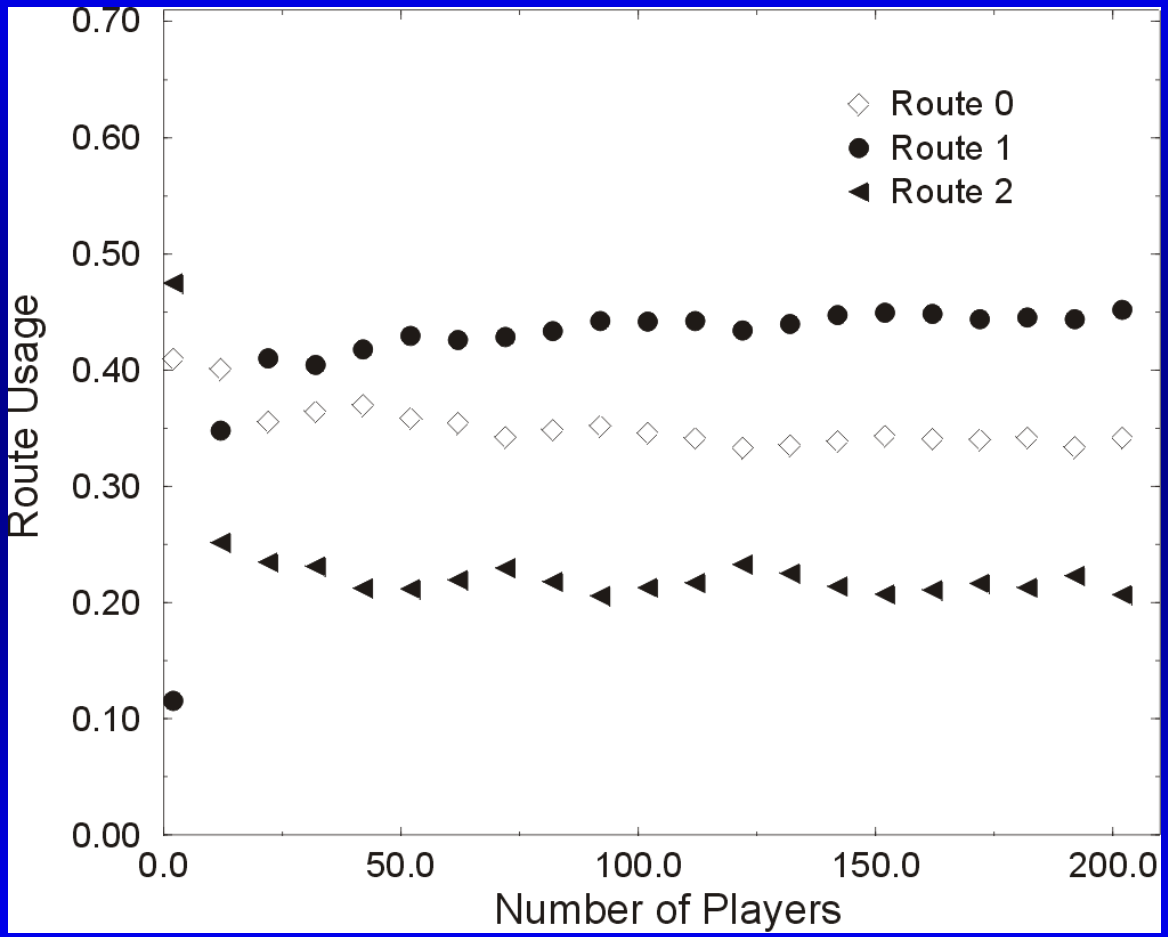


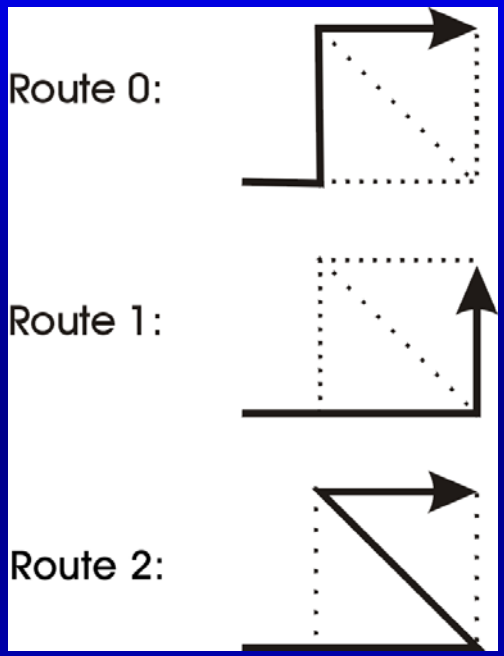
The Braess Paradox





Route Choice



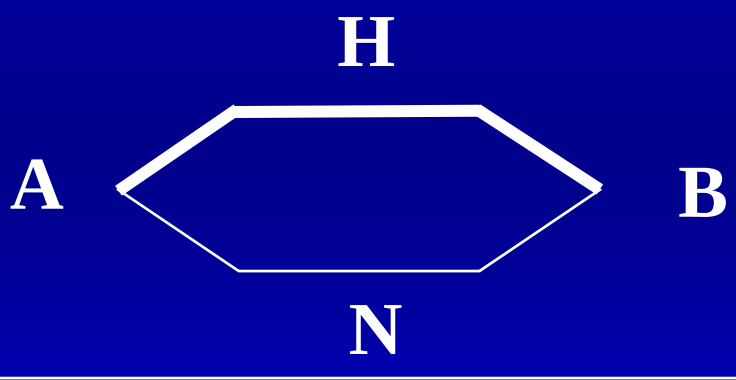


Day-to-Day Route Choice-Behaviour

Experimental design

Trip from **A** to **B**

Two routs **H** and **N** (**H** main, **N** side route)



Each of the 18 participants chooses in every round the main route **H** or the side route **N**.

Play it for 200 rounds.

Day-to-Day Route Choice-Behaviour

n_H: number of participants choosing H

n_N: number of participants choosing N

Travel times	
For H	$T_H = 6 + 2n_H$
For N	$T_N = 12 + 3n_N$

Payment per round: P = 40 - T	
$T = T_H$	For driver on H
$T = T_N$	For driver on N

Starting capital: 200

Payment = starting capital + sum of round payments

Change to real money

Day-to-Day Route Choice-Behaviour

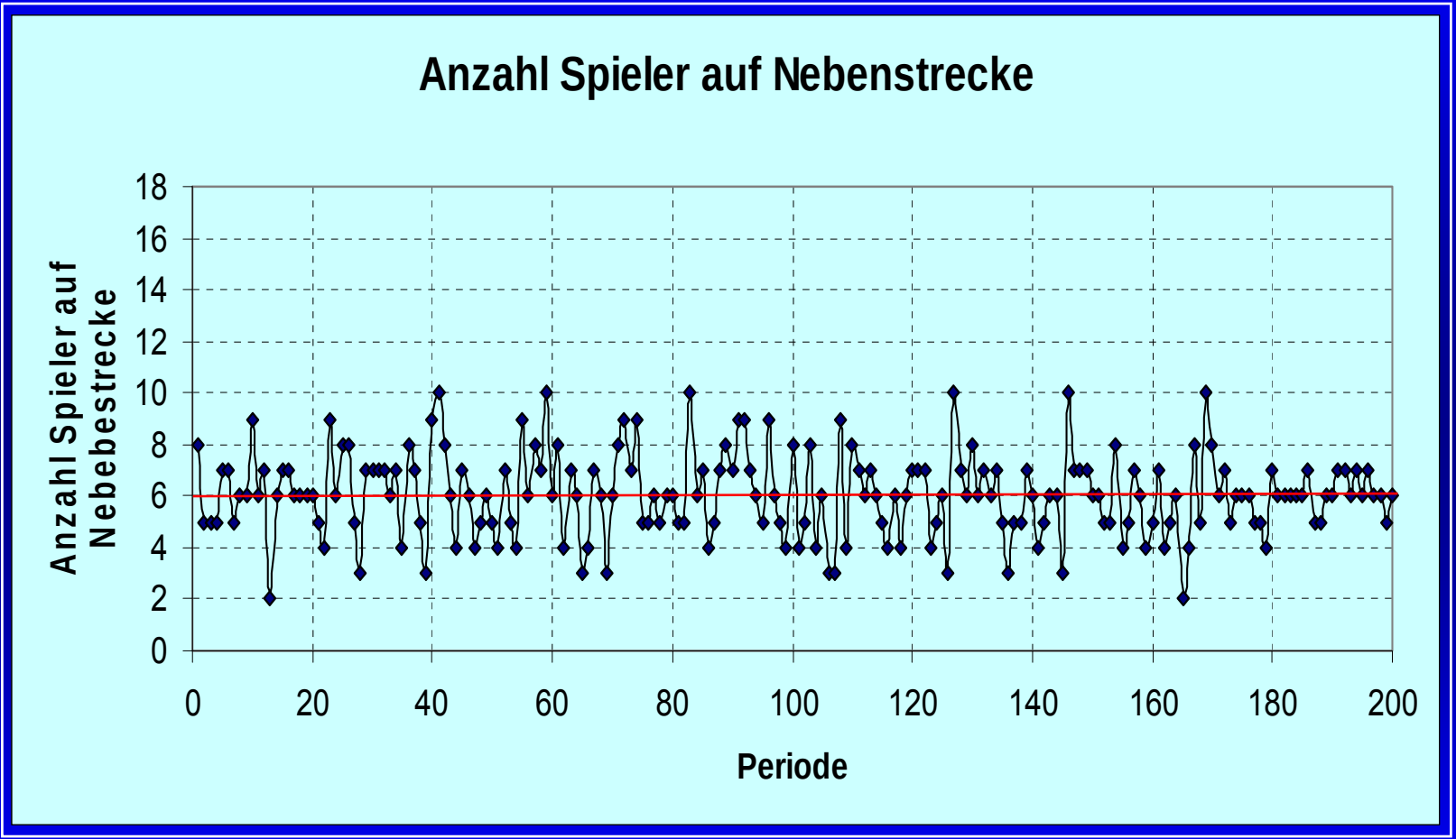
Informations of the players

6 rounds each

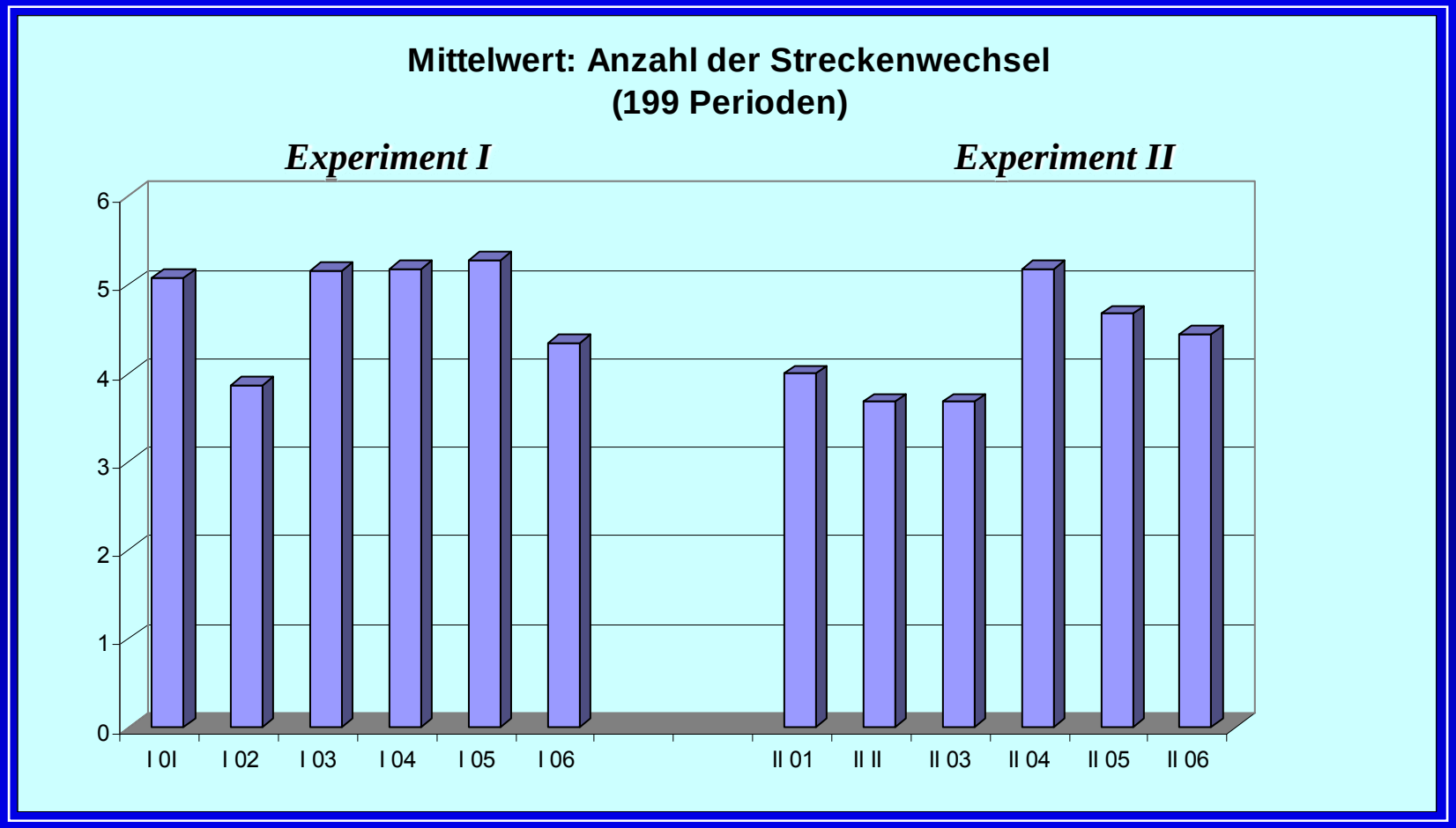
Informations: experiment I
Travel time in the last round for the chosen route.
Payment for the last round.
Total payment before the last round.
Running number of the last round.

Informations: experiment II (additional)
Travel time on the alternative route, which was not chosen in the last round.

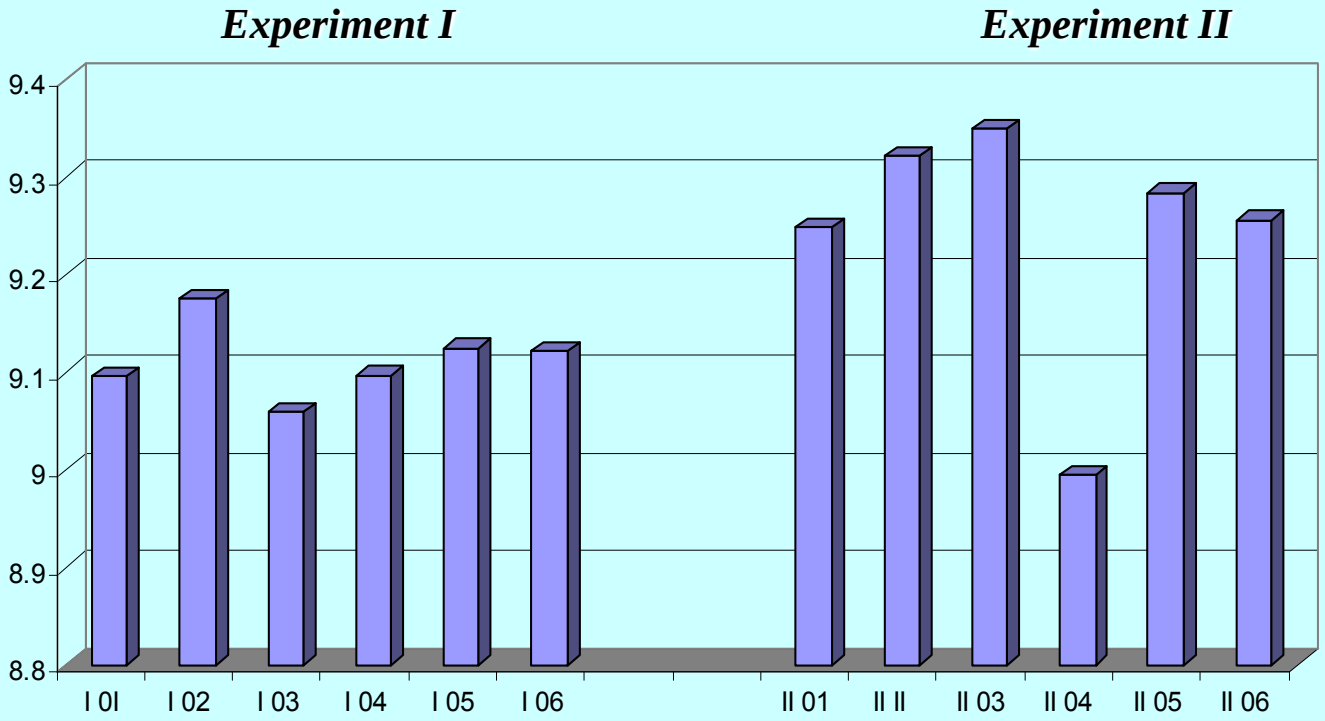
Day-to-Day Route Choice-Behaviour



Day-to-Day Route Choice-Behaviour



Day-to-Day Route Choice-Behaviour



Payoff Sum Model

Bush & Mosteller (1955), Harley (1981), Roth & Erev (1995)

Idea (‚Law of effect'):

Play with n participants and k pure strategies each.

Tendency at time t: $q_{nk}(t)$

If player n chooses strategy k at time t, he wins $x_{nk}(t)$ (units)

New tendency: $q_{nk}(t+1) = q_{nk}(t) + x_{nk}(t)$

Probability to choose strategy k in the next round:

$p_{nk}(t+1) = q_{nk}(t+1)/\text{sum}_l[q_{nl}(t+1)]$

q_{nk} is monotonously increasing with t and not bounded.

> as time goes on the learning effect becomes smaller ('flatter learning curves')

Day-to-Day Route Choice-Behaviour

Extended payoff sum model

Strategy vector

1	main road
2	side road
3	direct
4	contrarian

Simulations

Initial values (x_1, x_2, x_3, x_4)
$x_1 = 1,....,10$
$x_2 = 1,....,10$
$x_3 = 0,....,10$
$x_4 = 0,....,10$
1000 runs of 200 periods for each vector of initial values

[4,3,3,2] is the only vector of initial values with the property that the simulated means of the variables listed below are in the experimentally observed range.

	min Ex I & II	Simulations	max Ex I & II
mean(#(players[S]))	5.85	5.88	6.17
std_dev(#(players[S]))	1.53	1.65	1.94
mean(#(road_ch))	3.67	5.17	5.28
mean(#(last_road_ch))	154.78	183.73	190.39
mean(yule)	0.12	0.14	0.37
std_dev(yule)	0.52	0.60	0.74

Day-to-Day Route Choice-Behaviour

Extended payoff sum model

Variables

A_i	payoff sum for strategy i in period t
$A = A_1 + ,\ldots, + A_n$	total payoff sum
a	payoff for period t
A_i^+	next period's payoff sum for strategy i
p_i	probability of choosing i

Adjustment of payoff sum

$x_i > 0$ initial value for A_i in period 0

For $a \geq 0$: $$A_i^+ = \begin{cases} A_i + a & \text{if } i \text{ was chosen} \\ A_i & \text{else} \end{cases}$$

For $a < 0$: $$A_i^+ = \begin{cases} A_i & \text{if } i \text{ was chosen} \\ A_i + |a| & \text{else} \end{cases}$$

Probability of Choosing *i*

$$p_i = \frac{A_i}{A} \qquad i = 1,\ldots,n$$

Logistic version

$$p_i = \frac{e^{\lambda A_i}}{\sum_{j=1}^{n} e^{\lambda A_j}} \qquad \lambda > 0$$

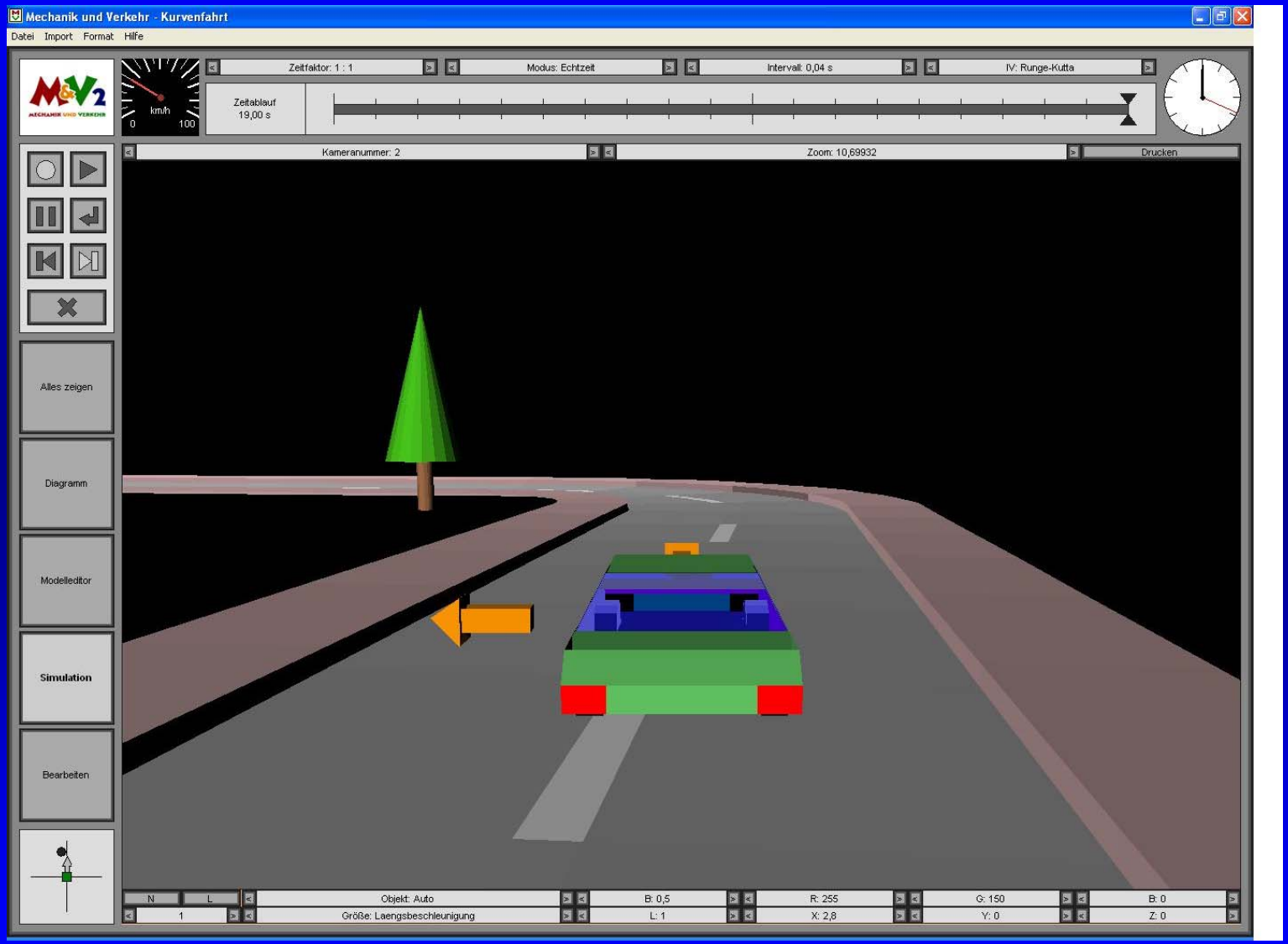
Day-to-Day Route Choice-Behaviour

Results

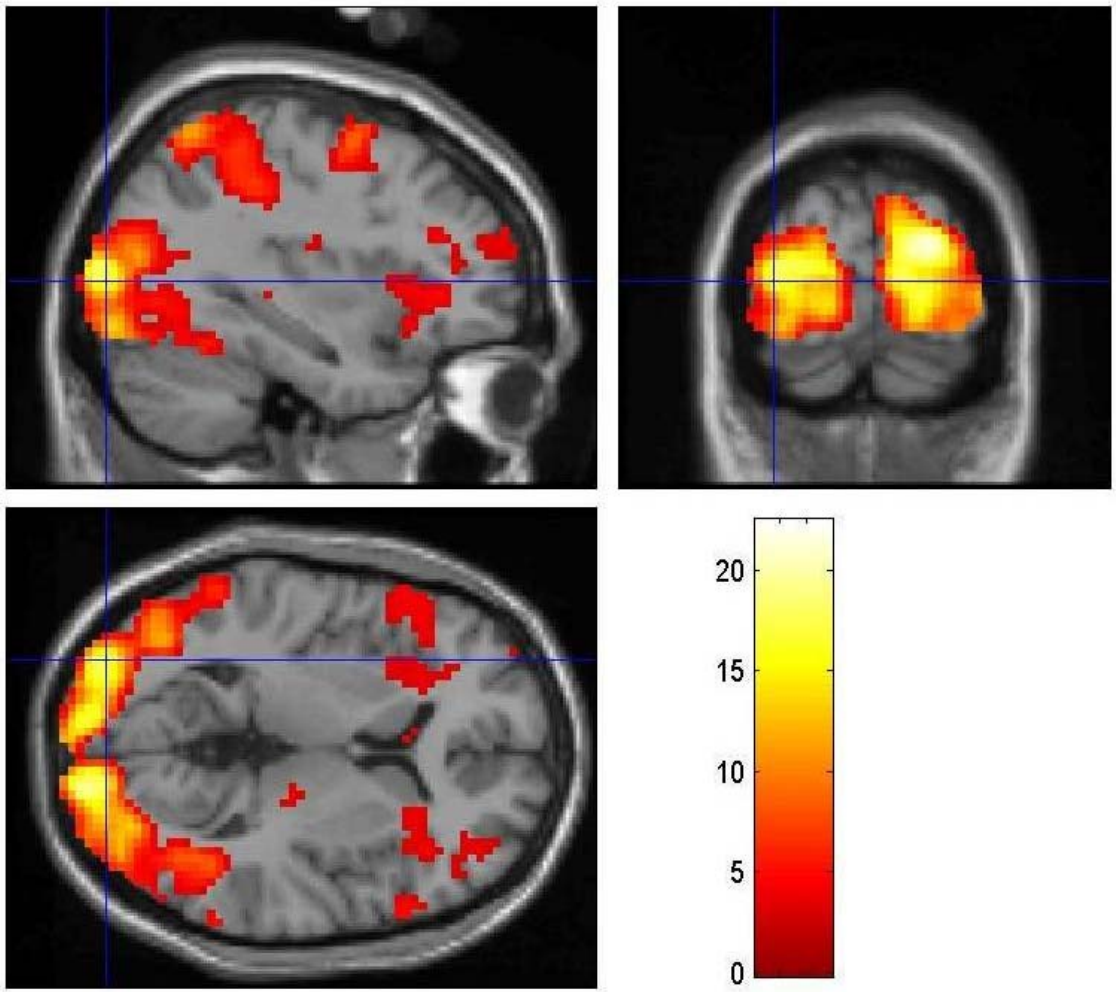
1. Mean number of players on main and side route is near to the equilibrium.
2. Fluctuations remain in both experiments up to the end.
3. Fluktuations are significantly lower in experiment II .
4. The total number of route changes ist significantly larger in experiment I.
5. Three typs can be classified: direct (“sensible“, 44%), contrarian (“tactical“, 14%) und conservative (“not sensible“, 40,5% und “stoical“, 1,5%).
6. The number of route changes and the payments are in all in all experiments negatively correleted.

fMRI

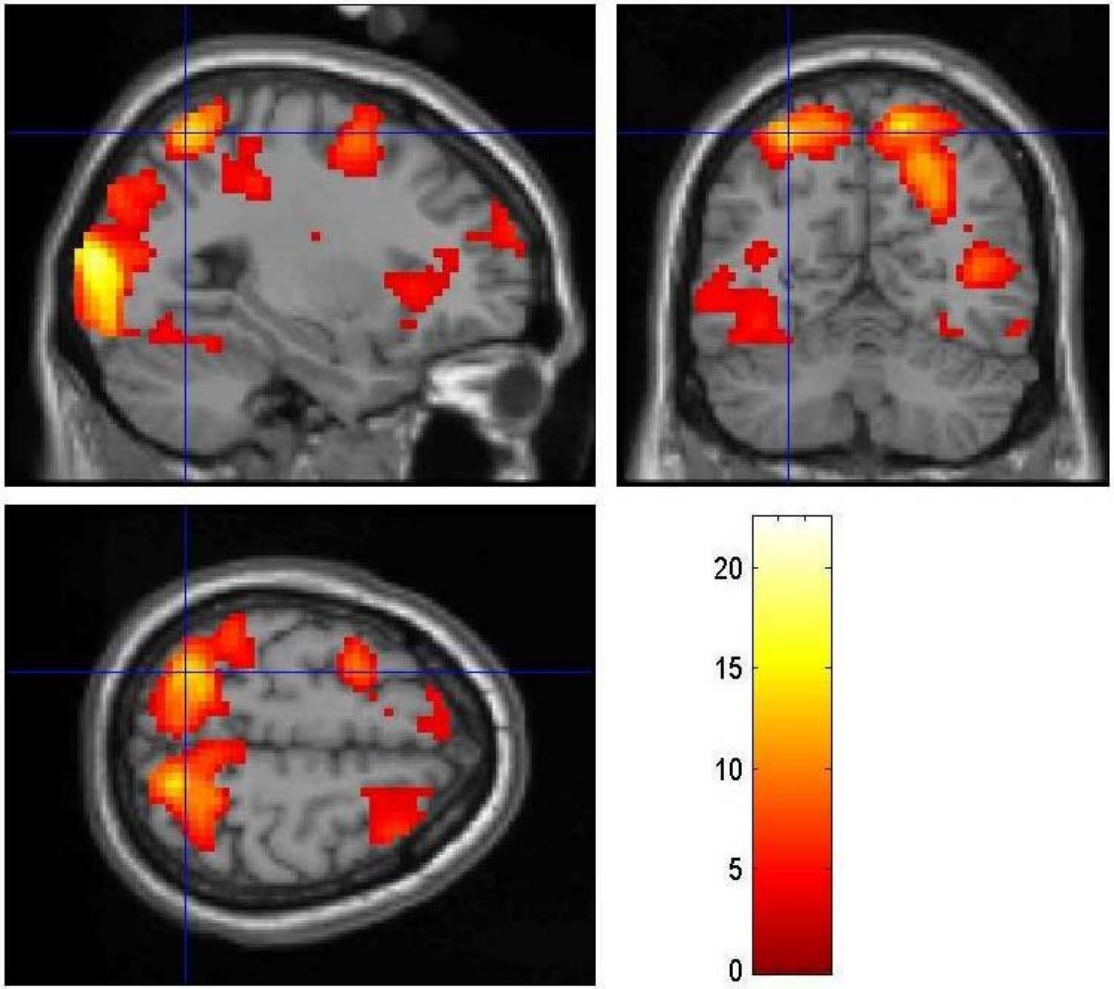
Simulation


Mechanik und Verkehr - Kurvenfahrt
Datei Import Format Hilfe
Zeitfaktor: 1 : 1
Modus: Echtzeit
Intervall: 0,04 s
IV: Runge-Kutta
Zeitablauf
19,00 s
km/h
0
100
Kameranummer: 2
Zoom: 10,69932
Drucken
Alles zeigen
Diagramm
Modelleditor
Simulation
Bearbeiten
N
L
Objekt: Auto
B: 0,5
R: 255
G: 150
B: 0
1
Größe: Laengsbeschleunigung
L: 1
X: 2,8
Y: 0
Z: 0

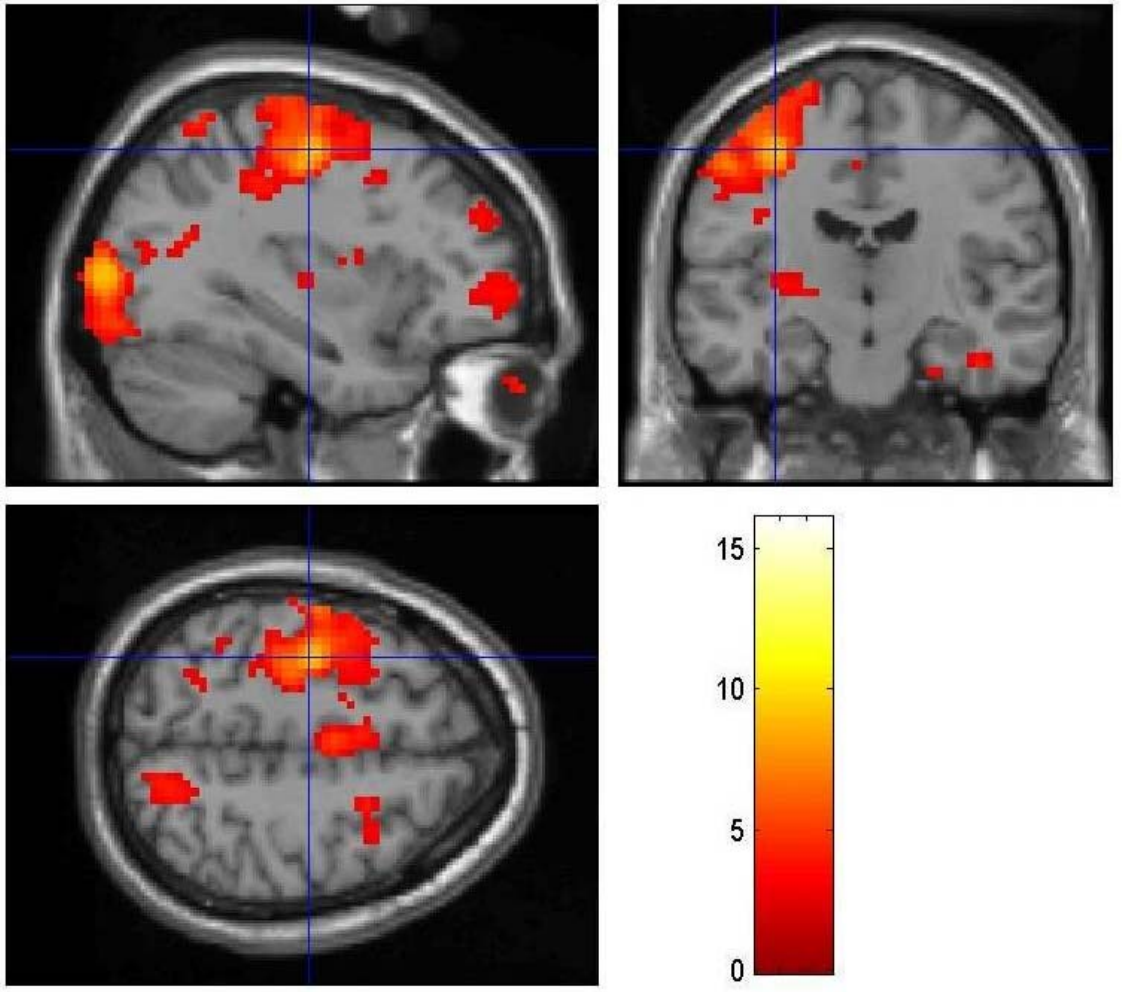
Looking



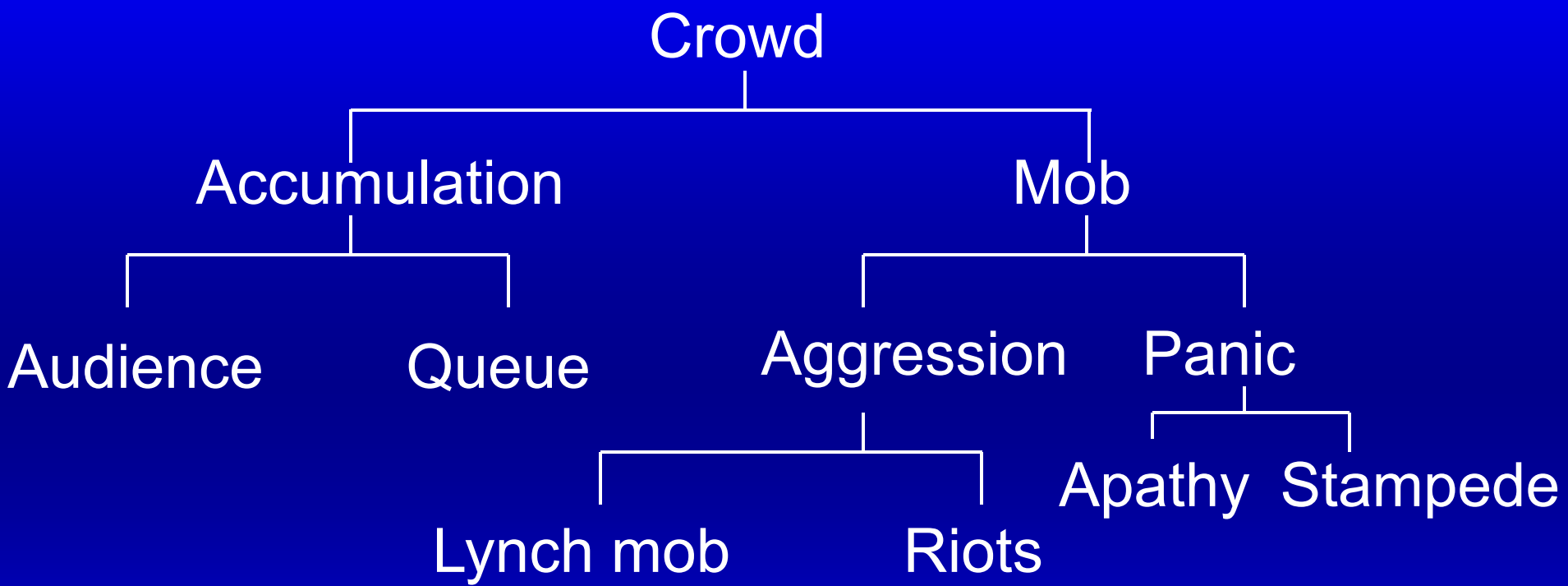
Looking



Driving



Terms

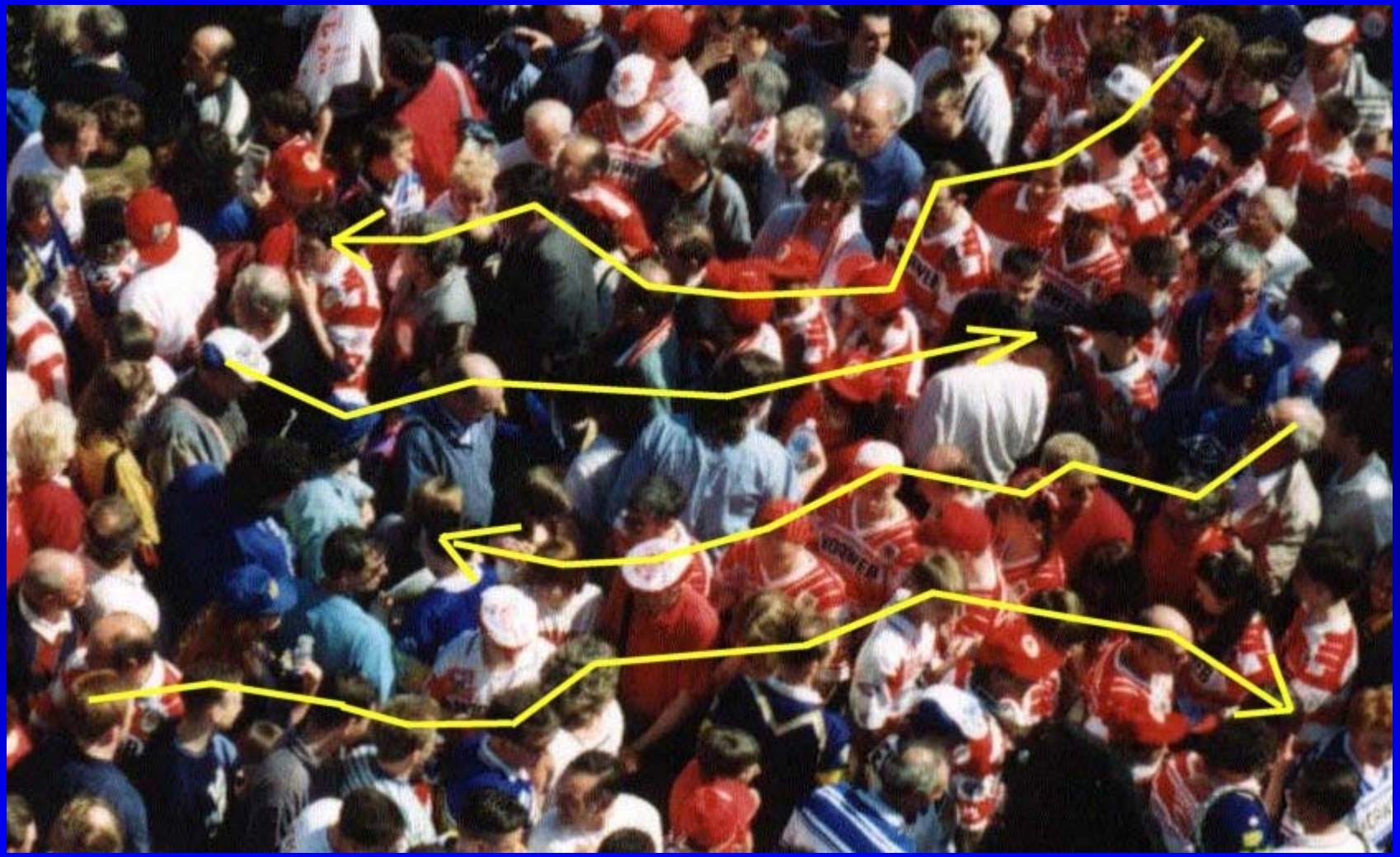

Crowd
Accumulation
Mob
Audience
Queue
Aggression
Panic
Lynch mob
Riots
Apathy
Stampede

Crowd Phenomena

Lane Formation

Jams and crowd

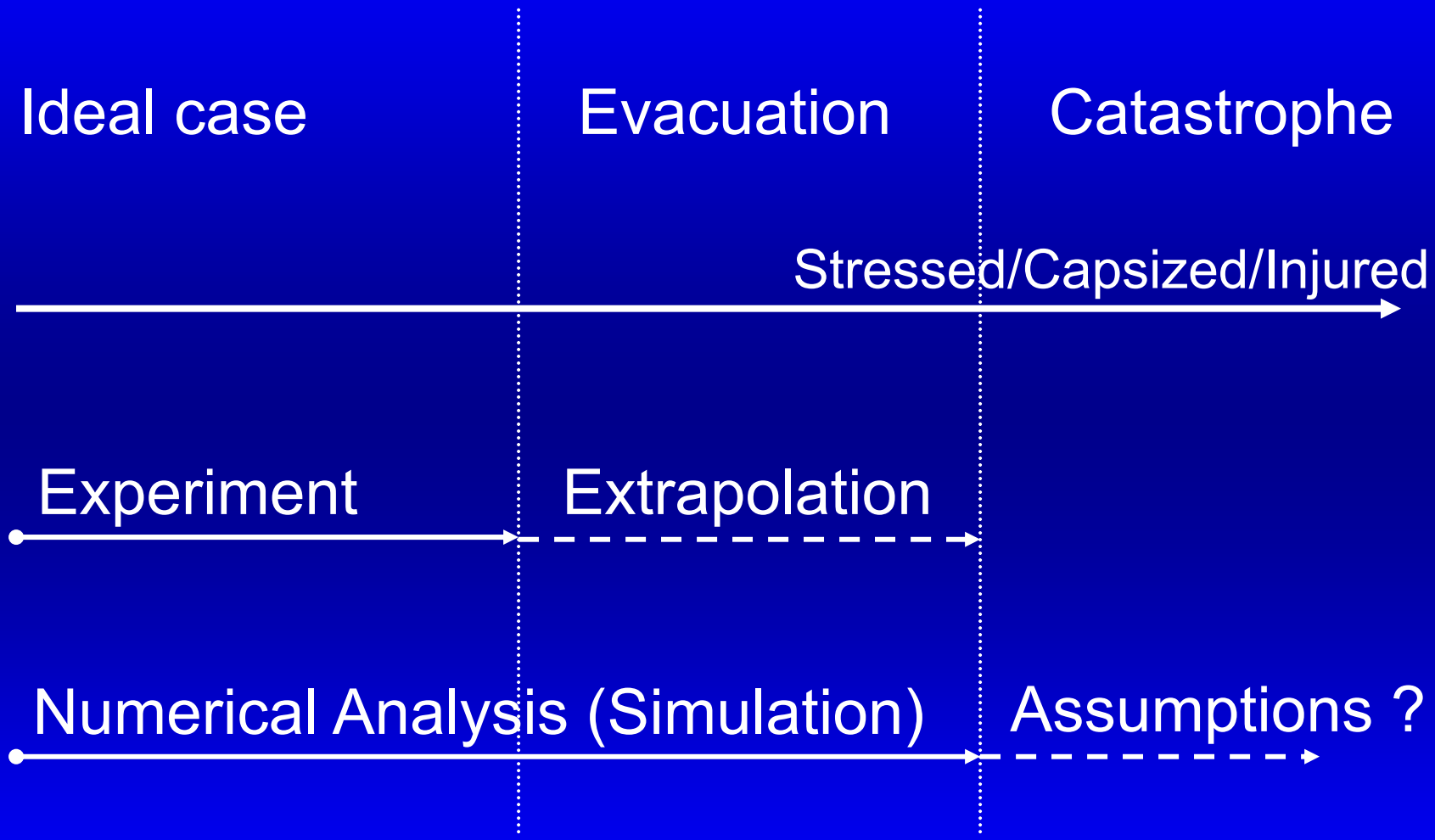
Lane Formation



Simulation?

(Waterpark Tokyo)

What is possible?



Pan I

Pan II

Consequences of Panic

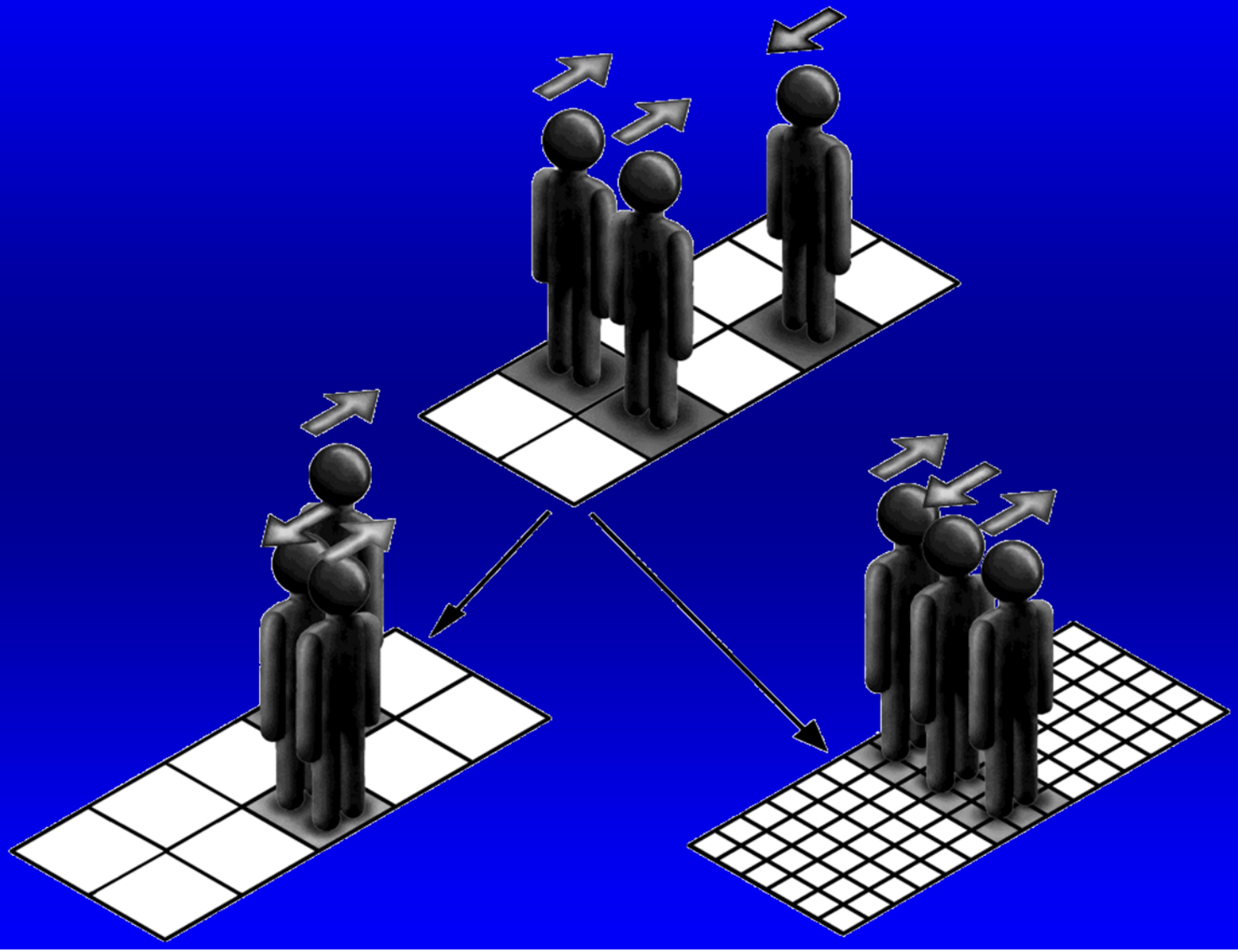
- Limited perception: tunnel look
- Herd instinct: attraction at larger distances
- Wet hands / feet > ...
- Blood flows from head / stomach into the motion musculature > desire to move
- Blood becomes thicker > faster formation of a scab
- Impatience > turning back
- Abolition of social connections (except own children)
- But also: passive panic > apathy

Evacuation of a Cinema

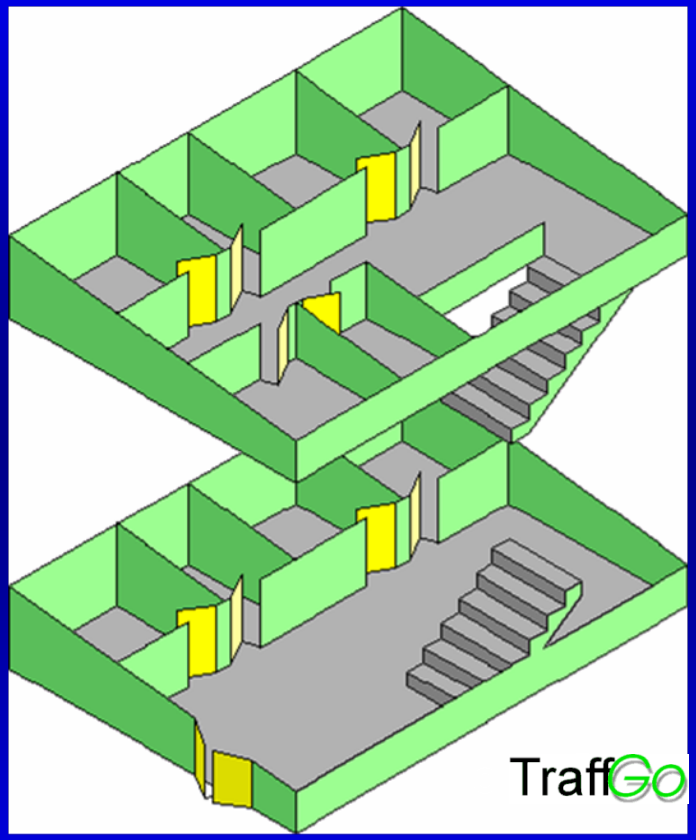
Simulation:
68 s

Reality:
66 s

Pedestrian Daynamics



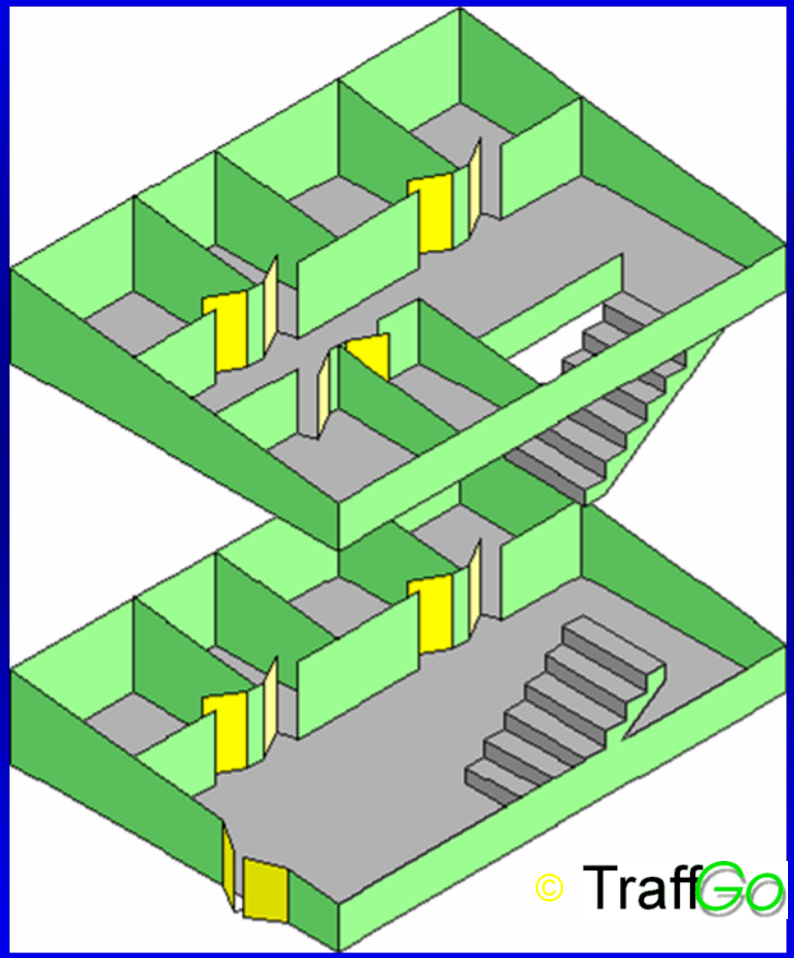
Simulation, Discretisation

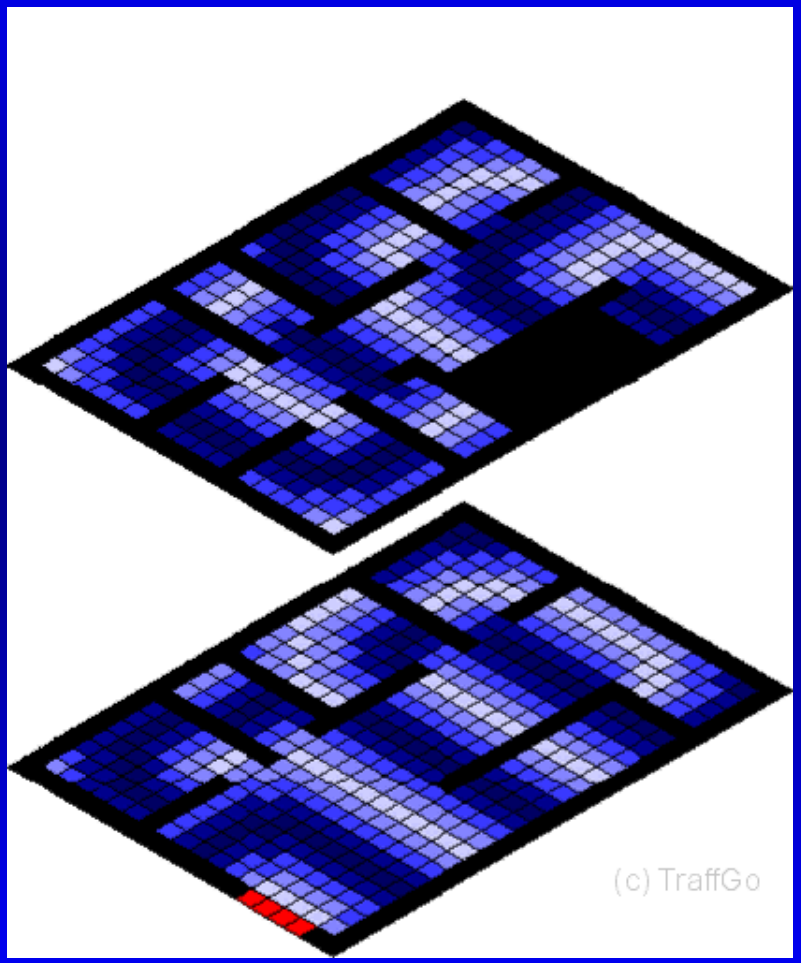


Zell size: 40 cm x 40 cm

- Available cells
- Blocked Cells
- Staircases
- Doors

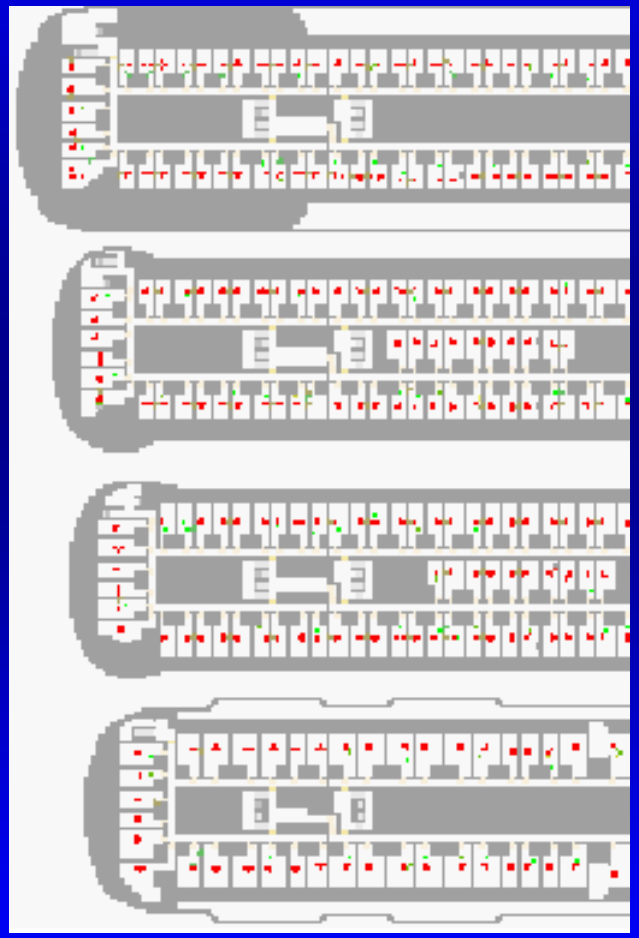
Simulation, Orientation

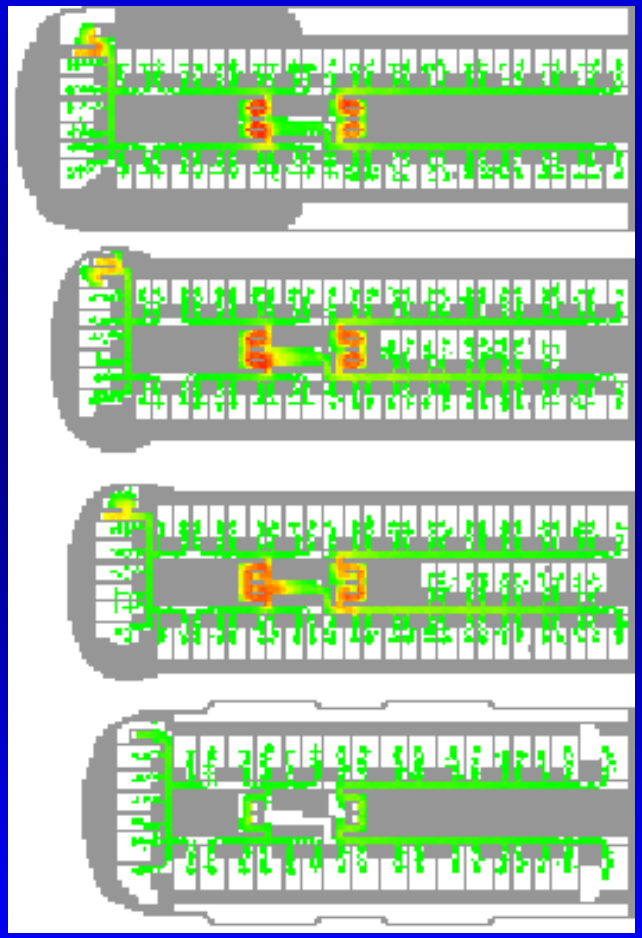




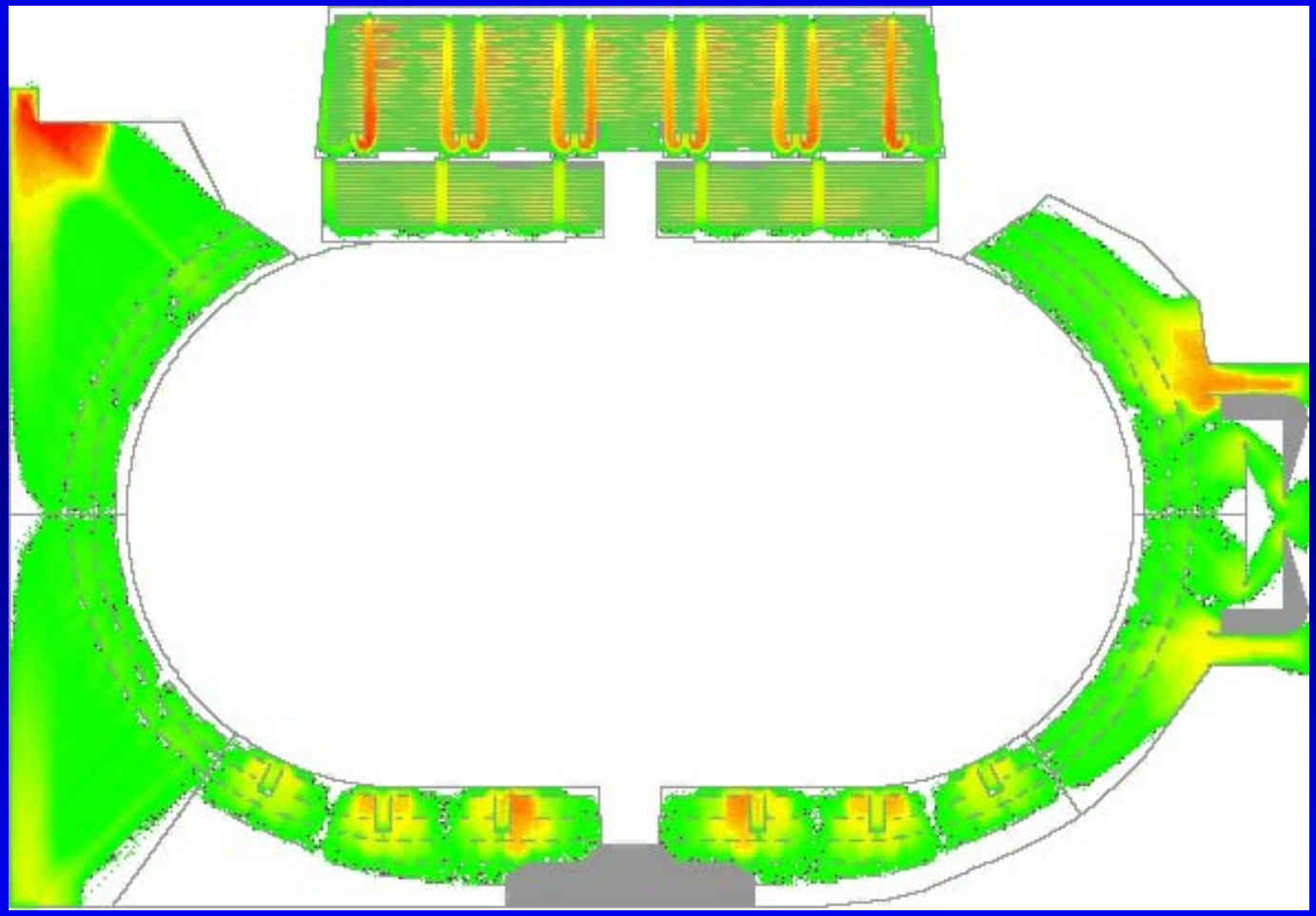
Example

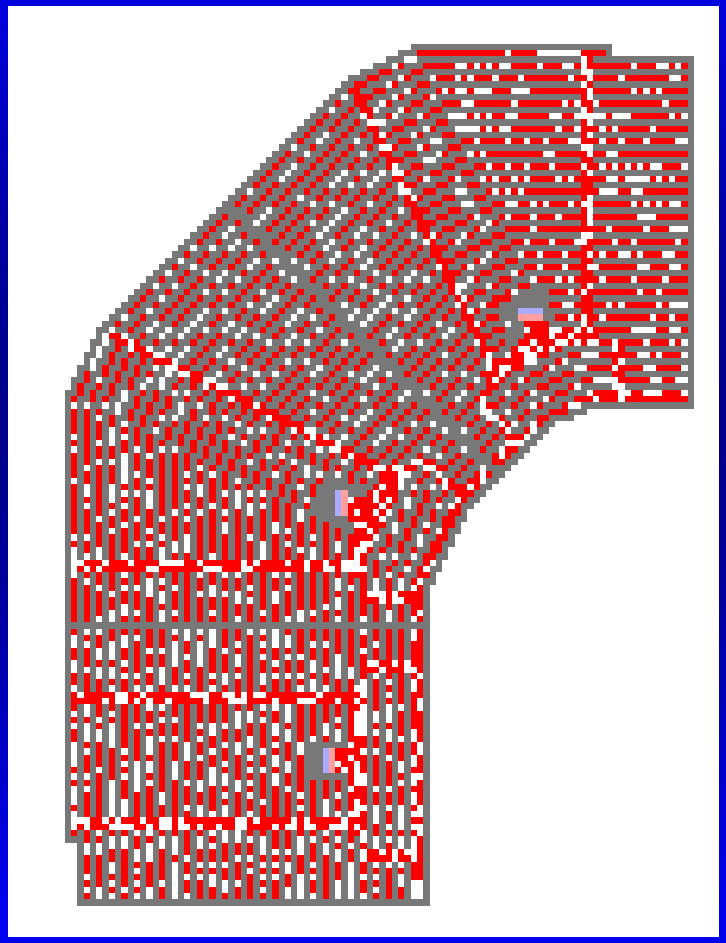
Passenger ship, 4 decks





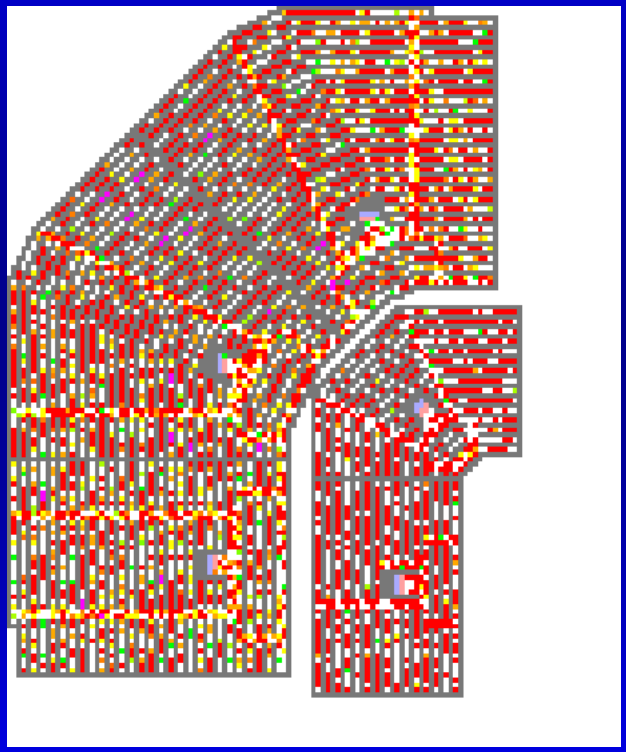
Evacuation of a Stadium





Comparison I

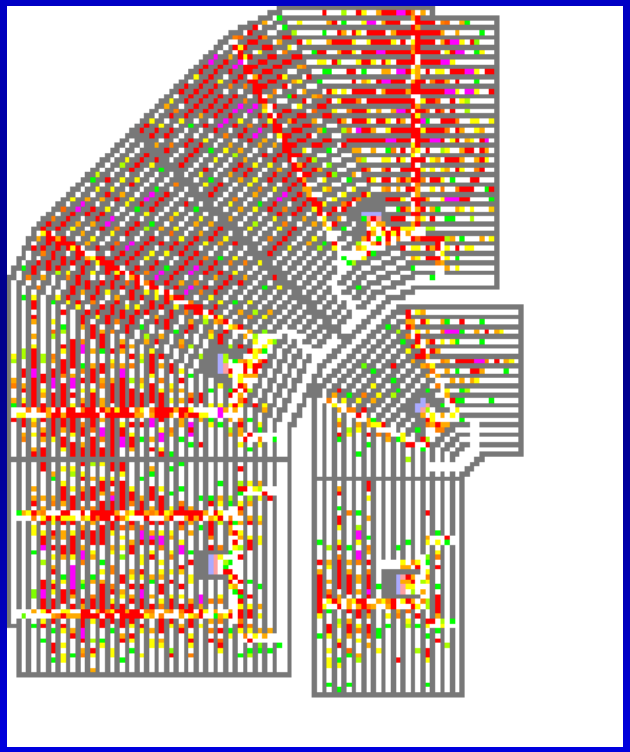
T = 2 Minuten



T = 20 Sekunden

Comparison II

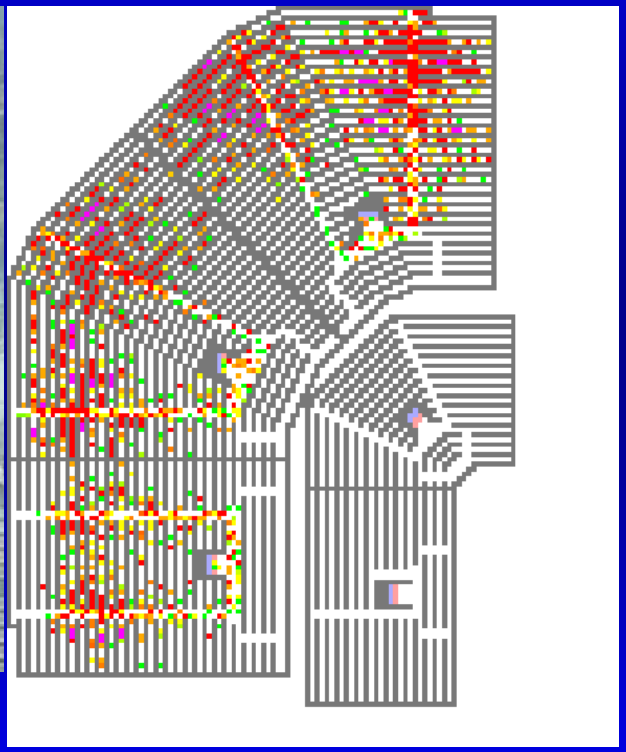
T = 5 Minuten



T = 3 Minuten

Comparison III

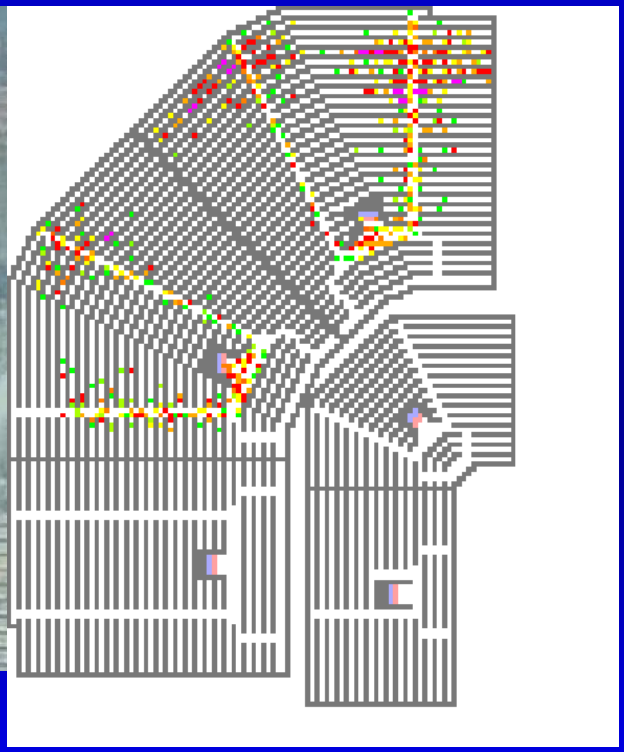
T = 7 Minuten



T = 6 Minuten

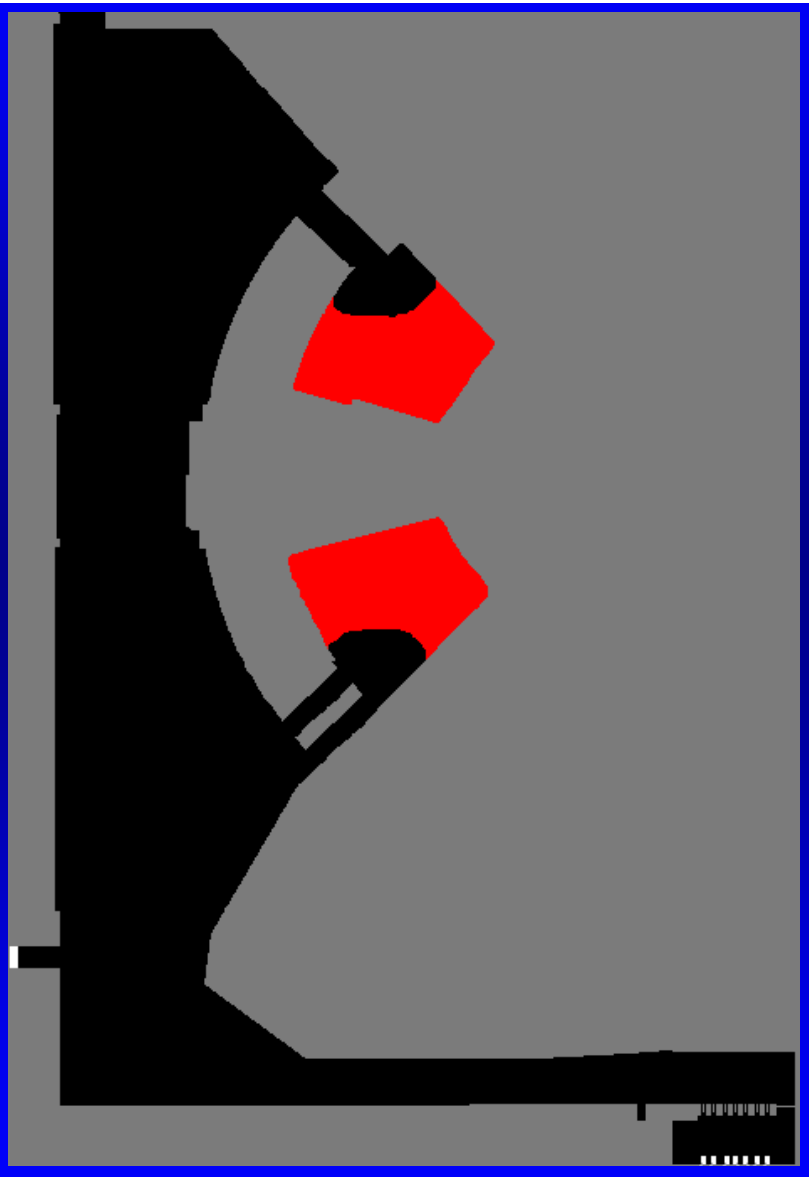
Comparison IV

T = 10 Minuten

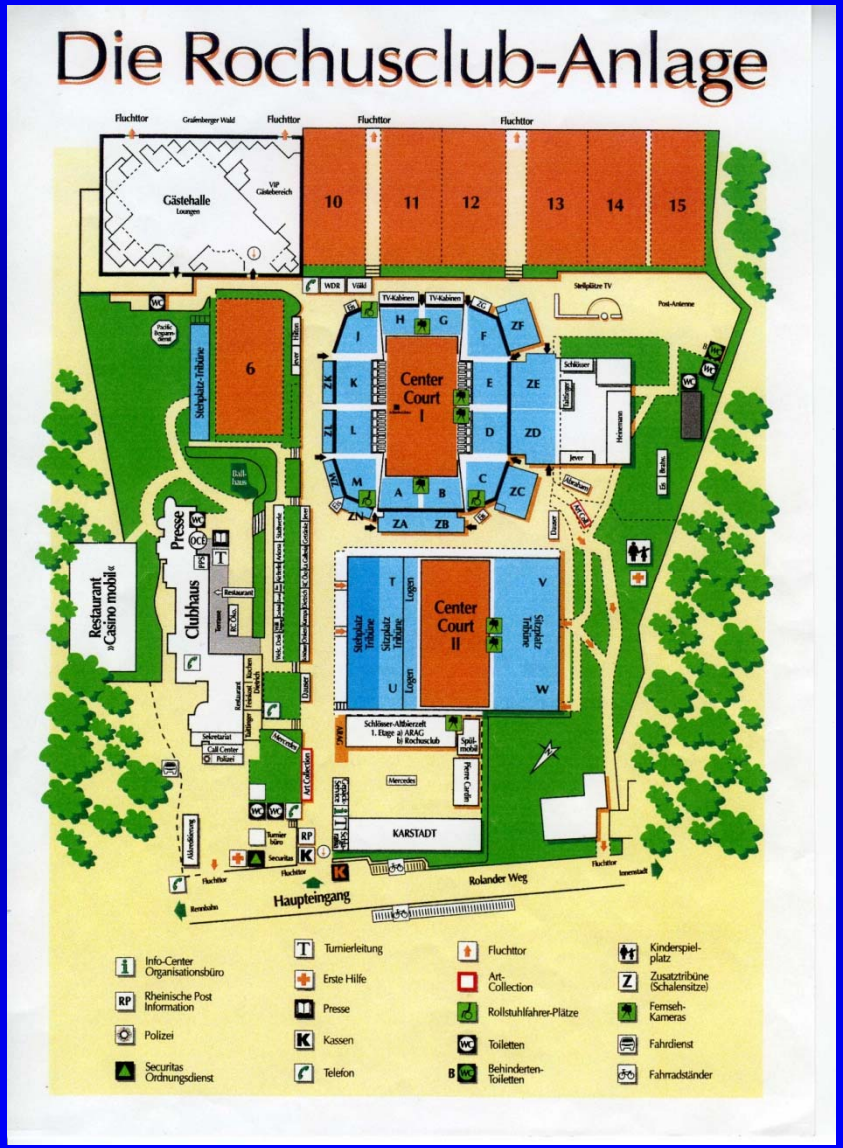


T = 10 Minuten

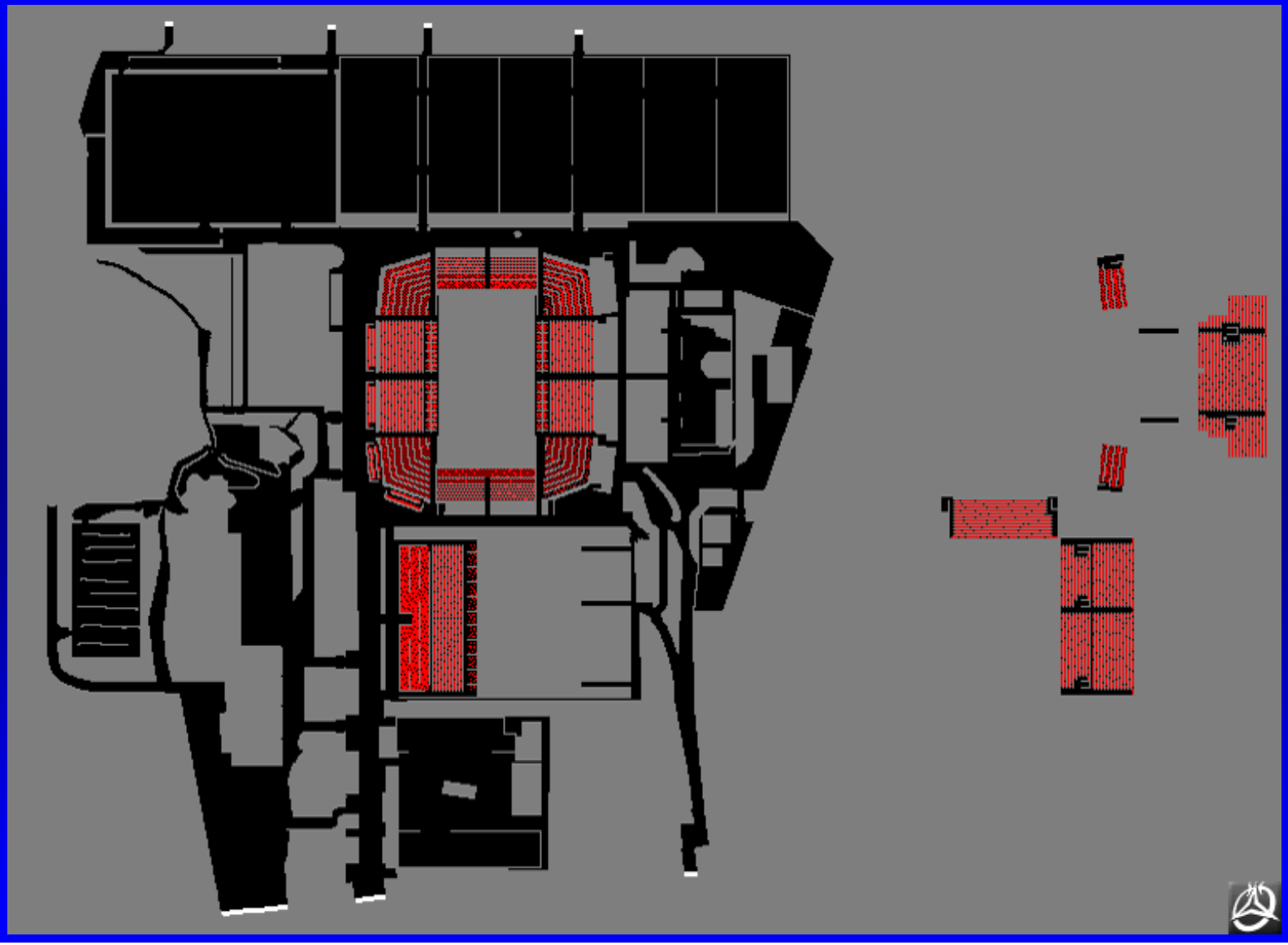
Berlin Stadium



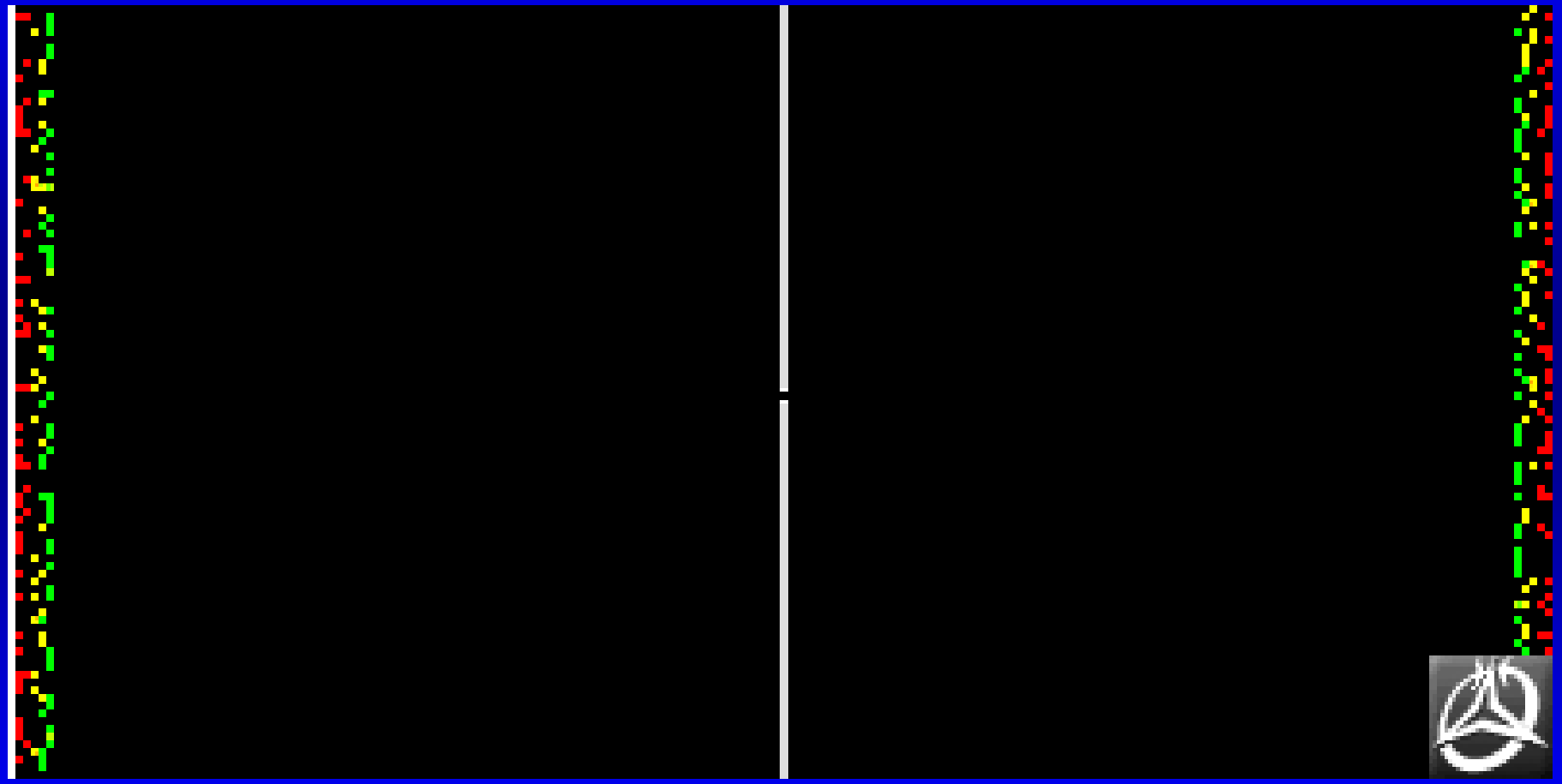
Rochusclub Düsseldorf



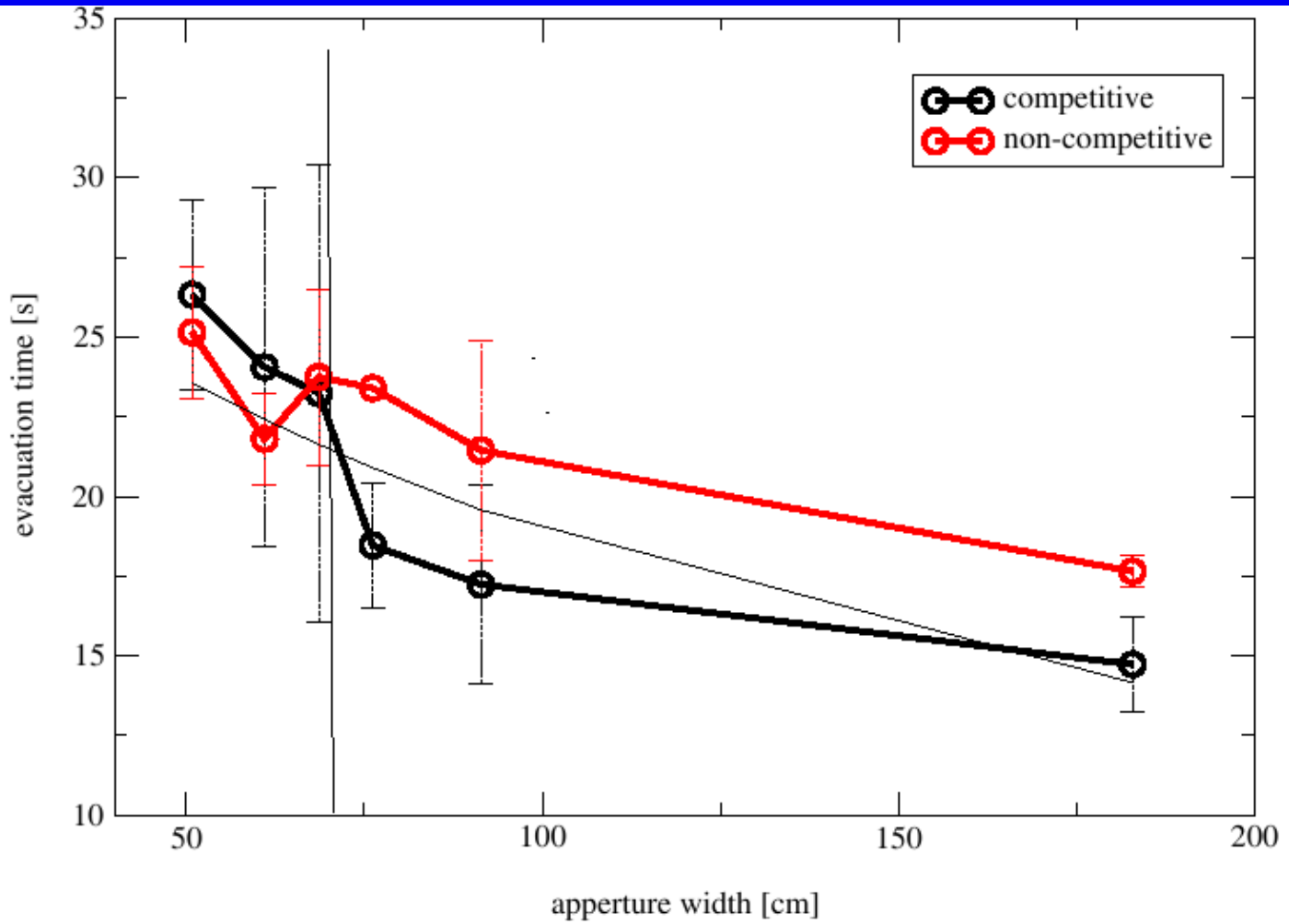
Tennis Arena



Bottleneck Counterflow



Competition

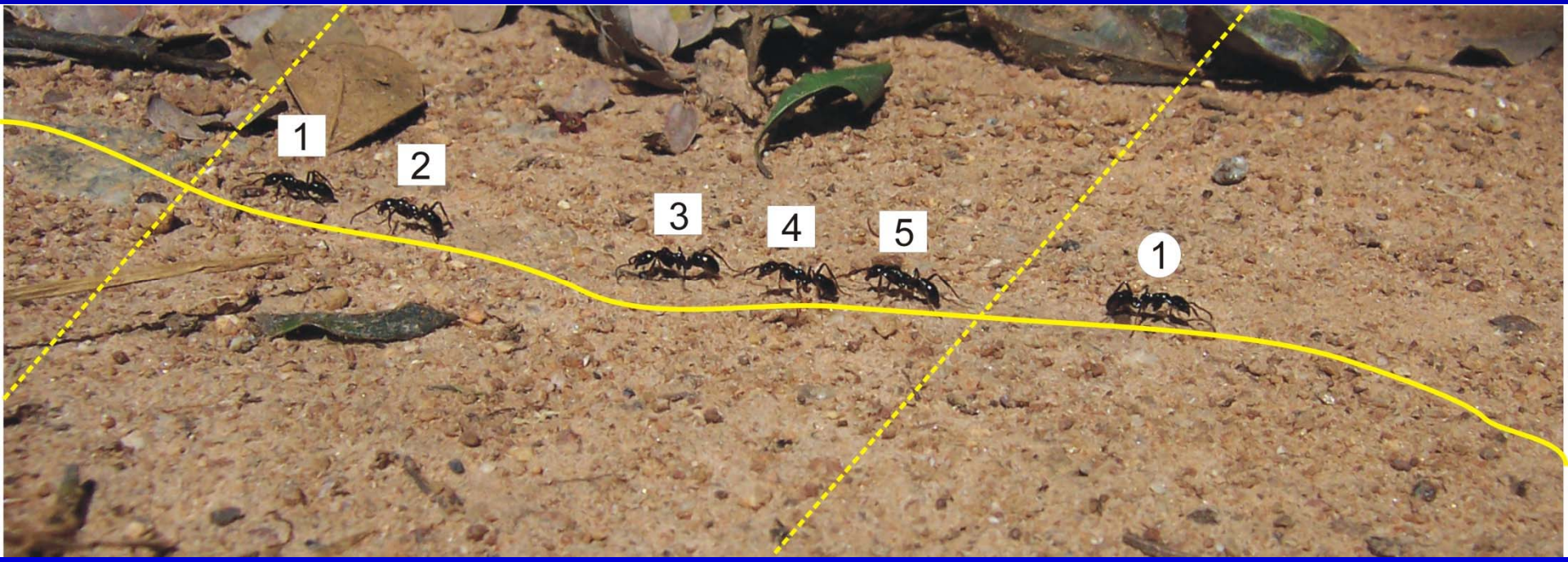


Hajj

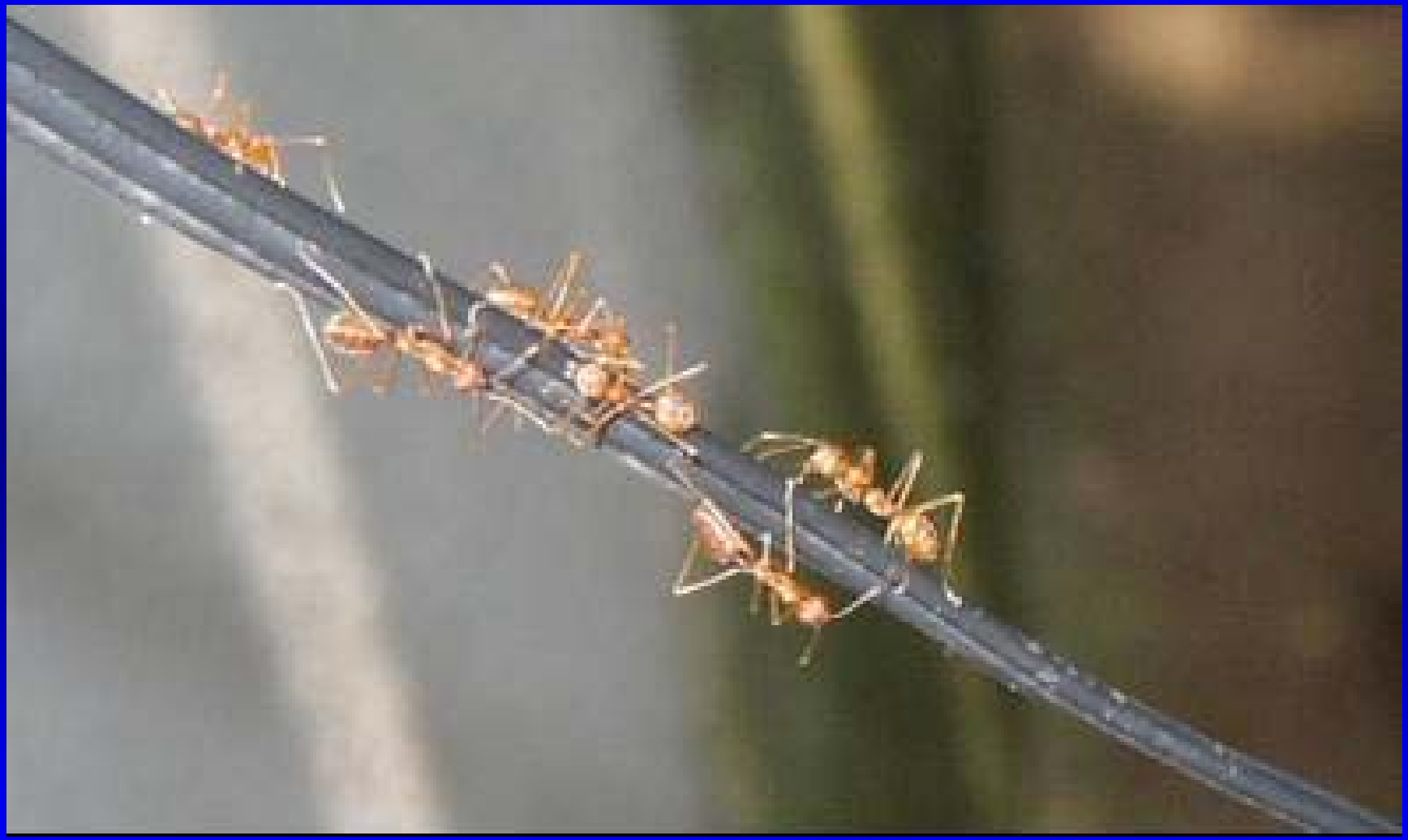
Hajj

Ant Traffic

Ant Traffic



Ant Traffic



Ant Accident

Ant Trails

http://www.ptt.uni-due.de

Conferences:

TGF ’09: 22 – 24 June 2009, Shanghai

PED ’10: 08 – 10 March 2010, Washington