Panta Rhei

More Quality of Traffic by centralized or decentralized Control ?!

Prof. Dr.-Ing. Dr. h. c. E. Schnieder

Overview

Traffic – System view
Control arrangements and objectives
Control problems, approaches and solutions

Heraclitus
(540 – 480 B.C.)

All things are in constant flux
Panta rhei
Traffic and its Contextual Environment

- politics / law
- human / society
- science
- technology
- ecology
- economy

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Traffic and its Axiomatic System Properties

state
traffic quality

structure
traffic elements

system
traffic

function
traffic organization

behavior
traffic processes

global | local
### Structuring of Traffic Control into Functions and Resources

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<th>Control Resources</th>
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<td>Truck dispatching</td>
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</table>

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- traffic flow increases to its global maximum, any further increase in density leads to instability and decrease of flow

- behavior expressed by the fundamental diagram may be denoted as suboptimal

- collective expression of drivers’ behavior
### Objectives and Means of Traffic Control

<table>
<thead>
<tr>
<th><strong>quality</strong></th>
<th><strong>means</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>global</td>
<td>local</td>
</tr>
<tr>
<td>increase safety</td>
<td>homogenization of driving behavior</td>
</tr>
<tr>
<td>increase capacity and flow</td>
<td>increase stability</td>
</tr>
<tr>
<td>decrease travel time and confidence</td>
<td>increase driver reliability</td>
</tr>
<tr>
<td>decrease fuel consumption</td>
<td>increase immediate intervention</td>
</tr>
<tr>
<td>decrease emission</td>
<td>measurement, control, actuating</td>
</tr>
</tbody>
</table>
Panta rhei - Fundamental decomposition of traffic control into function and ressources

Traffic Flow Interpretation - Microscopic and Macroscopic Traffic Flow Models

Microscopic level

Single vehicle $i$
- position $s_i$
- velocity $v_i$
...

Macroscopic level

- traffic flow $Q$
- traffic density $K$
- average velocity $v_m$

Source: tfhrc.gov, stadtentwicklung-berlin.com
Traffic Flow Interpretation - Microscopic and Macroscopic Traffic Flow Models

Panta rhei - Fundamental decomposition of traffic control into function and resources

Braunschweig, 17.08.2009
Panta rhei - Fundamental decomposition of traffic control into function and ressources

Traffic Flow Interpretation - Microscopic and Macroscopic Traffic Flow Models

Braunschweig, 17.08.2009
Panta rhei - Fundamental decomposition of traffic control into function and resources

Traffic Flow Interpretation - Microscopic and Macroscopic Traffic Measures

- **Microscopic Level**
  - Drivers and vehicle behavior
  - Road network
  - ADAS system behavior

- **Macroscopic Level**
  - Traffic flow $Q_{\text{real}}$
  - Traffic density $K_{\text{real}}$
  - Average velocity $v_{\text{real}}$

- **Reality**
  - Data collection
  - Verification

- **Simulation Model**
  - Car-following model
  - Lane-changing model
  - Network model
  - Single vehicle $i_{\text{real}}$
    - Position $s_{i_{\text{real}}}$
    - Velocity $v_{i_{\text{real}}}$
  - Single vehicle $i_{\text{sim}}$
    - Position $s_{i_{\text{sim}}}$
    - Velocity $v_{i_{\text{sim}}}$

**Fundamental Diagram, 07.05.2008**

Autobahn A2 Richtung Berlin, AS Lauenau

**Verification**

Braunschweig, 17.08.2009
# Fundamental Decomposition of Traffic Control into Function and Resources

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<td>Flow control</td>
</tr>
<tr>
<td></td>
<td>Traffic guidance</td>
</tr>
<tr>
<td></td>
<td>E.g. light-signal system or traffic message signs with induction loops</td>
</tr>
</tbody>
</table>

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Panta rhei - Centralized traffic control resources with global control functions

Central Problem of Traffic Flow Measurement

Panta rhei- Centralized traffic control resources with global control functions

Central Problem of Traffic Flow Measurement – Sampling Theorem


Braunschweig, 17.08.2009
### Panta rhei - Centralized traffic control resources with global control functions

Global and Local Control Functions / Performance Criteria

<table>
<thead>
<tr>
<th>performance criteria</th>
<th>ego vehicle</th>
<th>collective</th>
</tr>
</thead>
<tbody>
<tr>
<td>travel time</td>
<td>$T = \int_{s_0}^{s_{end}} dt \rightarrow \min$</td>
<td>traffic availability</td>
</tr>
<tr>
<td>arrival time</td>
<td>$\sigma_T \rightarrow \min$</td>
<td>traffic prediction</td>
</tr>
<tr>
<td>riding comfort</td>
<td>$\int_{s_0}^{s_{end}} a^2 dt \rightarrow \min$</td>
<td>homogeneity</td>
</tr>
<tr>
<td>fuel consumption</td>
<td>$\int_{s_0}^{s_{end}} P dt \rightarrow \min$</td>
<td>fuel consumption of the fleet</td>
</tr>
<tr>
<td>distance</td>
<td>$p(\Delta s = 0) \rightarrow 0$</td>
<td>traffic safety</td>
</tr>
<tr>
<td>overspeed</td>
<td>$p(v &gt; v_a) \rightarrow 0$</td>
<td></td>
</tr>
</tbody>
</table>

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### Traffic Control Objectives and Methodologies

<table>
<thead>
<tr>
<th>Objective</th>
<th>Considered Traffic Level</th>
<th>Methodologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>distance velocity</td>
<td>operational ego vehicle</td>
<td><strong>Local vehicle control</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• classical control e.g.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>− state space (Roppenecker et al.)</td>
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<tr>
<td></td>
<td></td>
<td>− frequency domain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• robust control e.g.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>− Sliding Mode Control [Utkin, Slotine]</td>
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<tr>
<td></td>
<td></td>
<td>− Quantitative Feedback Theory [Ackermann et al.]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>− $H_\infty$-Theory [Isidori et al.]</td>
</tr>
<tr>
<td>flow safety</td>
<td>tactical collective of vehicles / fleet</td>
<td><strong>Coordination of vehicles by cooperative control</strong></td>
</tr>
<tr>
<td>density</td>
<td></td>
<td>• potential fields [Ögren et al.]</td>
</tr>
<tr>
<td>quality</td>
<td></td>
<td>• Sliding Mode Control [Gazi et al.]</td>
</tr>
<tr>
<td>congestion</td>
<td></td>
<td>• Ljapunov-based [Jadbabaie et al.]</td>
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<td></td>
<td></td>
<td>• Receding-Horizon (MPC) [Jadbabaie]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• graph theory [Baillieul, Fax]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Distributed Consensus [Olfati-Saber, Fax, Murray]</td>
</tr>
<tr>
<td></td>
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<td>• Petri-Net decision making</td>
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**Braunschweig, 17.08.2009**
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for \( n \)-th order SISO system

definition of sliding surface \( S(t) \)

tracking means:

control law:

equivalent control via:

parameter \( k \) by stability criterion:

nominal (lin. single track) model

model uncertainty

design parameters

lin. optimization of

\[
\begin{align*}
\dot{\tilde{x}} &= \tilde{x} - \tilde{x}_d \\
s(x, t) &= \left( \frac{d}{dt} + \lambda \right)^{n-1} \tilde{x} \\
s(x, t) &= 0 \\
u &= u_{eq} - k \cdot \text{sat} \left( \frac{s}{\Phi} \right) \\
\dot{s}(x, t) &= 0 \\
s \cdot \dot{s} &\leq -\eta \cdot |s| \\
x &= \hat{f}(x) + b(x) \cdot u \\
F &= f - \hat{f} \\
\lambda, \eta, \Phi \\
J &= \frac{W_a}{N_a} \cdot \int a^2 \, dt + \frac{W_{Lw}}{N_{Lw}} \cdot \int \dot{\delta}_L^2 \, dt
\]
• Application e.g. for lateral vehicle-trailer control
  ➢ max. lateral deviation:
    • 15 cm – worst case scenario
    • 11 cm – wind gust at straight ahead driving
  ➢ stabilizes pendular oscillations due e.g. to cross winds
  ➢ may be used as a driver assistance system to provide driving safety

Example Simulation:
➢ velocity: 190 km/h
➢ straight ahead driving
➢ additionally: disturbance at steering angle as step of 15 deg. at $t=3 \text{ s}$
Specification of performance requirements by means of boundary function

**Boundary functions**

e.g. control variable

\[
\frac{u}{z_2} = \left| \frac{K(j\omega)}{1+GKM(j\omega)} \right| < W_5(\omega)
\]

Discretization of frequency
Panta rhei - Distributed control resources with local control functions
Local Control Principles - Quantitative Feedback Theory - Robustness Criteria

Family of plants:

\[ G(s) = \frac{k}{(s+a)(s+b)} \]

with \( k = [1..10] \), \( a = [1..5] \) und \( b = [20..30] \)

\[ G(s) = G_0(s)[1 + \Delta_M(s)] \]

- multiplicative uncertainty
- direct specification as function \( \Delta_M \)
- in form of virtual templates directly integrated into calculation of boundary curves

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physical structure of system

Block diagram of the controlled system

\[ \alpha_{gas} \rightarrow \text{engine} \rightarrow M_M \rightarrow \text{power train} \rightarrow M_D \rightarrow \text{wheel} \rightarrow F_{Fzg} \rightarrow \text{vehicle} \circlearrowright \]

\[ n_M \rightarrow n_{Rad} \rightarrow v_{Fzg} \]

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## Control Resources

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<tr>
<td></td>
<td>vehicle control</td>
<td>multi agent system</td>
</tr>
<tr>
<td></td>
<td>vehicle navigation</td>
<td>distributed consensus</td>
</tr>
<tr>
<td></td>
<td>level crossing control</td>
<td>combined with Petri nets</td>
</tr>
<tr>
<td><strong>Centralized</strong></td>
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<td></td>
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Agent

- autonomous entity
- goal-oriented and rule based
- pro-active and reactive
- cooperative and interactive
- mobile

Multi Agent System

- system of interacting agents
- complex system behavior based upon simple rules
- robust and scalable
Panta rhei - Distributed control resources with global control functions

- decision maker “on board”
- flexible usage of road capacity

- predetermined operation
- stringent allocation of track capacity (slots)

Realization for Road and Rail

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Panta rhei - Distributed control resources with global control functions
Realization for Rail
requirements to cooperative control methodology

- accomplish objectives for optimization of traffic behavior

- give a *mathematical framework* which
  - enables the engineer to model *perception and communication* between entities (vehicles)
  - integrates these to cooperative control-engineering
  - enables to analyze *robustness and performance* esp. with respect to
    - communication delays and data dropouts
    - formation stability, convergence

not supported but by Distributed Consensus (Graph Theory Based)
recent approach:
  - combination of Distributed Consensus and Petri-Net based decision making
Modeling the ad-hoc-network of C2C-communication by a graph $G(N,E)$

$N$ is a set of vehicles

$E$ is the ordered subset of the cartesian product $N \times N$

$$A = (a_{ij})_{i,j \in \{1,\ldots,p\}} \text{ with } a_{ij} = \begin{cases} 1 & \text{iff } (i, j) \in E \\ 0 & \text{else} \end{cases}$$

the adjacence matrix

Standard consensus algorithm

$$\dot{x}_i = -\sum_{j=1}^{n} a_{ij} (x_i - x_j)$$

$x_i$ denotes an arbitrary information variable that is exchanged between the vehicles

by the bidirectional graph the information variables converge at each vehicle to the average

This algorithm can be used for control
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Road Discretization - Petri net based Decision-Making

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Diagram showing the flow of traffic in two lanes, with arrows indicating the direction of movement.
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Road Discretization - Petrinet based Decision-Making

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## Objectives, Criteria and their Responsible and Demanding Parties

<table>
<thead>
<tr>
<th>Objective</th>
<th>Criteria</th>
<th>Party Responsible (interestent)</th>
<th>Party Concerned (demander)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ensuring traffic safety</td>
<td>Traffic safety (risk)</td>
<td>State, society</td>
<td>Traffic object, users of means of transportation, suppliers of infrastructure</td>
</tr>
<tr>
<td>Optimal economical benefit and minimum travel time, rapidness</td>
<td>Optimal transport expenses, parking costs, low amount of planning time,</td>
<td>Infrastructure, means of transportation producer, logistics, fleet manager</td>
<td>Sales market for end-user products and services, means of transportation user, traffic object</td>
</tr>
<tr>
<td></td>
<td>low travel time, dwell time of traffic jam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooperation, migration and integration</td>
<td>Net splitting, reachability of objectives, Park and Ride</td>
<td>Means of transportation supplier, infrastructure supplier, logistics, commodity supplier</td>
<td>Client, means of transportation user, logistic objects, logistician, society</td>
</tr>
<tr>
<td>Net load distribution and environmental protection</td>
<td>Load balancing, road damages, emissions</td>
<td>Policy, state, society, means of transportation producer and organiser</td>
<td>Means of transportation user</td>
</tr>
</tbody>
</table>
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A Mirical occurs

“Shouldn't we get a little more detailed in the implementation stage?“
Panta Rhei

More Quality of Traffic by decentralized Control !

Summary

Traffic – System view
Control arrangements and objectives
Control problems, approaches and solutions

Heraclitus
(540 – 480 A.C.)

All things are in constant flux

Prof. Dr.-Ing. Dr. h. c. E. Schnieder
traffic quality

traffic safety

congestion

flow

noise

density

distance

accidents

frequency

Meaning

Comprehension

Term

Properties

Value

Quantities

Characteristics
Ontologic Model of Transportation and Traffic Notions

- traffic
  - traffic organization
  - objects of transport
  - transport infrastructure
    - means of transportation
      - vehicles
      - trains
    - goods
    - persons
    - roads
    - tracks
  - environment

Methodology and tools
Safety models and description means

- Models
  - State independent failure sources
  - State dependent failure sources
    - Memoryless distributions
    - General distributions

- FMECA
- RBD
- FTA
- Markov chains
- Petri nets
- C++ (Monte-Carlo-Simulation)
Methodology and tools

Descriptions and results of the simulation

- FMECA
- RBD
- FTA

<table>
<thead>
<tr>
<th>Markov chains</th>
<th>Petri nets</th>
<th>C++ (Monte-Carlo-Simulation)</th>
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<tbody>
<tr>
<td>Availability, failure rates</td>
<td></td>
<td>accident severity</td>
</tr>
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Technical University of Braunschweig
Institute for Traffic Safety and Automation Engineering
Methodology and tools
Descriptions and results of the simulation

FMECA
RBD
FTA

- Isograph
- Relex
- Reliasoft
- Reliass
-...

Markov chains
- TimeNet
- CPN-Tools
- PiTool
-...

Petri nets
- Boost-Library
- MPI-Standard
- PVM
-...

C++ (Monte-Carlo-Simulation)
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