General Motors vision 76 years ago
Cyber = “Automatic radio control”
Physical = “Curved sides”
Outline

- Societal need and enabling technology
- Cyber-physical systems
- Scientific challenges
- Cyber-physical transportation systems
- Conclusions

D. J. C. MacKay. Sustainable Energy—without the hot air. UIT Cambridge, 2008

Load reduction
Load balancing
Energy consumption

- Industry: 35%
- Residential: 21%
- Commercial: 17%
- Transportation: 27%

Why now?

Enabling technology

- Sensing
- Communication
- Computation
From Information to Action Networks

- Internet
- WWW
- Ubiquitous computing

- Remote sensing
- Monitoring environments
- Wireless sensor networks

- Closing the loop
- Critical infrastructures
- Humans in the loop

Potential Savings with Smarter Systems

Transportation systems, buildings, and industry pollute and waste energy

Need for more and better sensing, monitoring, processing, optimization, and control

Smarter use of information and communication technology has great potentials:
- Predicted savings of up to 15% by 2020 (1990 levels)
- Emission reductions 5x the ICT sector’s own footprint
- Transportation can save 2.2 GtCO$_2$e

How to improve resource efficiency?

Load reduction

Load shifting

Peak shaving

Outline

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Cyber-physical systems are engineered systems whose operations are monitored and controlled by a computing and communication core embedded in objects and structures in the physical environment.
Cyber-physical systems

Mobile access devices

Cyber infrastructure

Ubiquitous physical interactions

Cyber-physical systems applications

Intelligent Transportation

Smart Buildings

Personalized Media

Urban Planning

Health & Wellbeing

Process Industry

Information and Communication Technology

Smart Grid

Urban Planning
Cyber-physical systems are engineered systems whose operations are monitored and controlled by a computing and communication core embedded in objects and structures in the physical environment.

Cyber-physical systems challenges

**Societal Scale**
- Global and dense instrumentation of physical phenomena
- Interacting with a computational environment: closing the loop
- Security, privacy, usability

**Distributed Services**
- Self-configuring, self-optimization
- Reliable performance despite uncertain components, resilient aggregation

**Programming the Ensemble**
- Local rules with guaranteed global behavior
- Distributing control with limited information

**Network Architectures**
- Heterogeneous systems: local sensor/actuator networks and wide-area networks
- Self-organizing multi-hop, resilient, energy-efficient routing
- Limited storage, noisy channels

**Real-Time Operating Systems**
- Extensive resource-constrained concurrency
- Modularity and data-driven physics-based modeling

**1000 Radios per Person**
- Low-power processors, radio communication, encryption
- Coordinated resource management, spectrum efficiency

Sastry & J, 2010
How to tame the complexity?

Technological and Physical Complexity

Cyber-Physical Systems

Human and Social Complexity

Multi-Layer Dynamic Network Models

Cognitive & Human

Optimization & Control

Information & Communication
Outline

• Societal need and enabling technology
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The transportation system is a cyber-physical system
Mainly without global control and optimization

Demands from Goods Road Transportation

- Road transport consumes 26% of total EU energy and accounts for 18% of greenhouse emissions
- 45% of all freight transport is on roads
- Emissions increased by 21% for 1990-2009


Life cycle cost for European heavy-duty vehicle

- 24% of long haulage trucks run empty
- 57% average load capacity

Dr. H. Ludanek, CTO, Scania

Schitler, 2003; Scania, 2012
Technology Push

Sensor and communication technology

Real-time traffic information

Vehicle platooning and autonomous driving

Heavy-Duty Vehicle Platooning

Rapport on vehicle platooning developed by KTH and Scania (Oct, 2011)

PhD student Assad Alam on Discovery Channel (Jan, 2012)
The Physics

Liang (2014)
Air Drag Reduction in Truck Platooning

10% fuel reduction potential

\[ F_{\text{air}} = \frac{1}{2} c_D(d) A_w \rho_w v^2 \]

Relative distance in platoon [m]


Fuel-Optimized Goods Transport

- Goods transported between cities over highway network
- 19 000 000 light+medium+heavy trucks in China
- 2 000 000 heavy trucks in European Union (400 000 in Germany)
- Large distributed control systems with no real-time coordination today

**Goal:** Maximize total amount of platooning with limited intervention in vehicle speed and route

Larson et al., 2013
Functional Architecture for Goods Transport

Alam et al., 2012
On-board platoon coordinator
• Coordinate platoon creation, merge, split etc
• Optimize platoon speed
• Interact with cruise controllers

Off-board transport planner
• Monitor trucks and traffic
• Choose routes to maximize platooning
• Replan due to new trucks, weather, changing traffic conditions, etc
Receding Horizon Cruise Control for Single Vehicle

Adjust driving force to **minimize fuel consumption based on road topology** info:

The total fuel consumption over time $T$ is:

$$f_c = \int_0^T \delta(t) (\frac{1}{m} \frac{dv}{dt} + mg \cos \alpha + mg \sin \alpha) \, dt$$

Require knowledge of road grade $\alpha$, not available in today’s navigators

$$\frac{dv}{dt} = F_{mg} - F_h - F_{ad} (v, d) - F_y (\alpha) - F_g (\alpha)$$
$$= F_{mg} - F_h - \frac{1}{2} \rho A_c v^2 \phi (d)$$
$$- mg \cos \alpha - mg \sin \alpha$$

Implemented as velocity reference change in adaptive cruise controller

Alam et al., 2011

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Distributed Road Grade Estimation

**RMS Road Grade Error**

Aggregated N=10, 100, 1000 profiles of lengths 50 to 500 km

Sahlholm, 2011
Vehicle System Architecture

Data from other vehicles
Own position and velocity
Pos from vehicle ahead

CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control
EMS – Engine management system
BMS – Brake management system
GMS – Gear management system

Platoon System Architecture

CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

Alam et al., 2014
Fuel-efficient and Safe Vehicle Platooning

- Jointly minimize fuel consumption for a platoon of vehicles
- Keep small relative distances under strict safety constraints

Turri et al., 2015

Experimental Evaluation

Alam, 2014
Experiments **without** Platoon Coordinator and Look-ahead Road Grade Information

Simulations **with** Platoon Coordinator and Look-ahead Road Grade Information
Evaluation of Energy Efficiency

CC: First vehicle runs conventional cruise controller, second tries to keep fixed time gap
LAC: First vehicle runs instead look-ahead cruise controller, second still keeps fixed time gap
CLAC: Vehicles run cooperative look-ahead control with platoon coordinator

When and where to create platoons?

Goal: Maximize total amount of platooning with limited intervention in vehicle speed and route

Larson et al., 2013
Platoon merge and split

Heavy-duty vehicle traffic without platooning

Merge and split platoons at highway intersections

Only vehicles that are relatively close in space and time platoon

Larson et al., 2013

Distributed optimization of platooning

Heavy-duty vehicle traffic without platooning

With platooning

Predictive control decisions at road intersections on whether it is beneficial for a vehicle to catch up another vehicle at next intersection

Larson et al., 2013
Numerical evaluations

- German road network with 300 trucks
- Random starting points and destinations
- 500 experiments

2-5% deployment enough for substantial benefit

Fuel saved compared to shortest path

Fuel saved vs total no of vehicles

Larson et al., 2013

Infrastructure for data collection

Data base for data analysis

C200 Vehicle data

T_s=10 min
Feasibility Study Based on Real Truck Data

- Position snapshot May 14 2013
- 7,634 Scania trucks
- 500,000 km² in Europe

- Positions sampled every 10 min
- Trajectories of 14 trucks

- 875 long-haulage trucks over European region
- Trucks close in time and space (< r m) could adjust speed to platoon and then save 10% fuel during platooning

Spontaneous vs Coordinated Platooning

- Paths of 1,773 trucks
- Trucks within 100 m from another truck

Larson et al., 2013
Liang et al., 2014
Spontaneous vs **Coordinated** Platooning

Adjust truck departure times

<table>
<thead>
<tr>
<th>Individual trucks</th>
<th>Platoons of 2-5 trucks</th>
<th>Platoons of 6-10 trucks</th>
<th>Platoons of 11-25 trucks</th>
<th>Platoons of &gt;25 trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time interval</td>
<td>Fuel saved*</td>
<td>Platooning rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 min</td>
<td>0.68%</td>
<td>13.22%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 min</td>
<td>1.19%</td>
<td>22.41%</td>
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</tr>
<tr>
<td>15 min</td>
<td>1.64%</td>
<td>30.26%</td>
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</tr>
<tr>
<td>30 min</td>
<td>2.74%</td>
<td>47.58%</td>
<td></td>
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</tr>
<tr>
<td>1 hr</td>
<td>4.31%</td>
<td>68.07%</td>
<td></td>
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</tr>
<tr>
<td>2 hr</td>
<td>5.94%</td>
<td>83.23%</td>
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<tr>
<td>3 hr</td>
<td>6.87%</td>
<td>89.93%</td>
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<td></td>
</tr>
<tr>
<td>6 hr</td>
<td>8.06%</td>
<td>95.67%</td>
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</tr>
<tr>
<td>12 hr</td>
<td>8.85%</td>
<td>98.38%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 hr</td>
<td>9.37%</td>
<td>99.38%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Coordinated departure times enable much more platooning**

Liang et al., 2014

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**Stockholm-Zwolle (1300 km) 24/7 Testing**

**Evaluation studies**
- Platooning in real traffic
- Fuel reductions and safety
- Driver acceptance
- Public acceptance

Stockholm Transport Lab
Internal haulage company
20 trucks, 360,000 km/year
75 trailers, 92% loaded
65 drivers, 40 h work/week
How willing are drivers to platoon?

- Jan-Apr 2013 experimental evaluation
- Drivers in the loop with advanced ACC (radar etc)
- Encouraged but not enforced to platoon
- Notable fuel reductions

Scania Transport Lab
Internal haulage company
20 trucks, 360,000 km/year
76 trailers, 92% loaded
65 drivers, 40 h work/week

Cyber-physical-human system

- Collaborating drivers
- Operator supervision
- Traffic flow optimization
- Autonomous vehicle platoons
- Wireless communication infrastructure
- Vehicle-to-vehicle information flows
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Conclusions

- **Cyber-physical systems to tackle grand societal challenges**
  - Real-time control of infrastructure resources
- **Optimized cooperative driving for goods transportation**
  - High-level optimization and scheduling of transport
  - Low-level control and coordination of truck platoons
- **Open problems**
  - Global vs local objectives: Who owns the performance metric?
  - Local computing vs communication: When do it in the Cloud?
- **Large-scale testing and evaluations**

http://people.kth.se/~kallej
Acknowledgments

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Per Sahlholm

Jonas Mårtensson
Bart Besselink
Valerio Turri
Sebastian van de Hoef
Farhad Farokhi
Jeff Larson
Håkan Terelius
Ather Gattami
Control of Vehicle Platoons

On the Optimal Error Regulation of a String of Moving Vehicles

PATH platoon demo San Diego 1997

Demo for Dutch Minister of Infrastructure and the Environment Ms Schultz van Haegen
Collaborative Cruise Control

- How to jointly minimize fuel consumption for a platoon of vehicles?
  - Keep small relative distances vs. close to individual optimal trajectories?
  - Uphill and downhill segments; heavy and light vehicles

Dynamics of vehicle $i$ depend on distance $d_{i-1,i}$ to vehicle $i-1$:

\[
\begin{align*}
\frac{dd_{i-1,i}}{dt} &= v_{i-1} - v_i \\
\frac{du_i}{dt} &= F_{\text{eng}}(d_i, \omega_i) - F_{\text{brake}} - F_{\text{drag}}(v_i, d_{i-1,i}) - F_{\text{roll}}(\alpha_i) - F_{\text{gravity}}(\alpha_i) \\
&= k_i(T_i, \omega_i) - F_{\text{brake}} - k_i^p\nu_i f_i(d_{i-1,i}) - k_i^p \cos \alpha_i - k_i^p \sin \alpha_i
\end{align*}
\]

Higher efficiency thanks to improved control and coordination of energy use

D. J. C. MacKay. Sustainable Energy—without the hot air. UIT Cambridge, 2008

UK energy consumption per day and person

Energy inputs: 125 kWh/d
- Heating: 40 kWh/d
- Transport: 40 kWh/d
- Electrical things: 18 kWh/d
- Losses in conversion to electricity

2008
Cyber-Physical Security

Need **analysis and design tools** to understand and mitigate attacks

- Which threats should we care about?
- Which resources are more important to protect?
- What impact can we expect of an attack?
- How to create resilient systems?

**Cross-disciplinary** research agenda

- IT security (authentication, encryption, firewalls, etc.) is needed, but not sufficient
- Malicious actions can enter in the control loop, even if channels are secure

**Grand societal challenges**

- Impact on future infrastructure systems where everything is connected
- Systems need to be trusted by the general public