Traffic Management for the 21st Century

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1. WHY TRAFFIC MANAGEMENT (TM)?

- Motorised road vehicle: A highly influential invention \(\Rightarrow\) Vehicular traffic
- Vehicles share the road infrastructure among them, as well as with other (vulnerable) users: TM needed
- Few vehicles: Static TM for safety
- Many vehicles: Dynamic TM for efficiency
Basic elements of an automatic control system

Technology (Sensors, communications, computing, actuators): Skeleton
Methodology (Data processing, control strategy): Intelligence
Current TM Systems (ITS)

- **Process**: conventional vehicle flow
- **Sensors**: spot sensors (loops, vision, magnetometers, radar, ...)
- **Communications**: wired
- **Computing**: distributed/hierarchical
- **Actuators**: road-side (TS, RM, VSL, VMS, ...)
2. EMERGING VACS (Vehicle Automation and Communication Systems)

- Significant efforts: Automotive industry, Research community, Government agencies
- Mostly vehicle-centric: safety, convenience
- In-vehicle systems (automated vehicles), e.g. ACC
- V2I or cooperative systems (connected vehicles), e.g. CACC
Future TM Systems (C-ITS)

- **Process**: enhanced-capability vehicle flow
- **Sensors**: vehicle-based
- **Communications**: wireless, V2V, V2I, I2V
- **Computing**: massively distributed
- **Actuators**: in-vehicle, individual commands
Implications/Exploitation for traffic flow efficiency?

- **TRAMAN21**: TRAffic MANagement for the 21st Century (ERC Advanced Investigator Grant)
  
Intelligent vehicles may lead to dumb traffic flow (efficiency decrease ⇒ congestion increase)

Why?
- ACC with long gap (⇒ capacity)…
- … or sluggish acceleration (⇒ capacity drop)
- Conservative lane-change or merge assistants
- Underutilized dedicated lanes
- Inefficient lane assignment
- Uncoordinated route advice
- …

What needs to be done in advance/parallel to VACS developments?
3. MODELLING

- Currently not sufficient traffic-level penetration of VACS → no real data available
- Analysis of implications of VACS for traffic flow behaviour
- Also needed for design and testing of traffic control strategies
- Microscopic/Macroscopic traffic flow modelling
Microscopic Modelling

- **No ready available tools**
- **Research** (open-source) tools: documentation, GUI, …
  - e.g. **SUMO**: an expanding open-source tool (DLR, Germany)
- **Commercial** tools: closed; or elementary coding of VACS functions
ACC traffic efficiency

Macroscopic Modelling

- Few research works
- Different penetration rates
- Macroscopic lane-based models
- Validation based on microscopic simulation data
4. MONITORING/ESTIMATION

- **Prerequisite** for real-time traffic control
- Conventional detectors are:
  - spot sensors (*local* information)
  - costly (to acquire, install, maintain)
- Exploitation of **new real-time information** from connected vehicles:
  - abundant in space
  - “cost-free” → ask TomTom, Google, Gaode, …
  - suffices for *speed* and *travel time*
  - not for total *flow* or *density*
- **Mixed** traffic, various penetration levels
- **Fusion** with conventional detector data
- **Reduction** (...replacement) of infrastructure-based sensors
- **OD** estimation
- **Incident** detection
Freeway traffic estimation scheme

Urban road/network traffic estimation
(with new data)

- Road queue length estimation
- Total flow estimation
  - Data fusion with conventional detectors
- Paradigm shift in signal control:
  - Strongly reduced (or no) detector hardware, cost for real-time signal control
  - Performance evaluation for fixed signals update
5. TRAFFIC CONTROL

- Which conventional traffic control measures can be taken over? – In what form?
- Which new opportunities arise for more efficient traffic control?
  - Increased control granularity (e.g. by lane, by destination, flow splitting)
  - Arbitrary space-time resolution
  - Efficient lane assignment
- Various control levels: vehicle, local, link, network
Vehicle-level tasks

- What is the movement strategy of automated cars? (in a manually driven world)
- How would traffic look like if all vehicles were automated?
- Can automated cars be exploited as actuators to improve the traffic flow?
- **Space-time dependent** change (control) of vehicle behaviour?
  - ACC gap and acceleration
  - Lane-changing behaviour
- Vehicle **trajectory** control
Vehicle-optimal advancement versus Traffic-optimising vehicle behaviour
Real-time **ACC Time-Gap Control** (section-based)

\[ T_{stg,i}(k) = \begin{cases} 
T_i[q_i(k)] & \text{if } v_i(k) > v_{\text{cong}} \\
T_{\text{min}} & \text{at active bottlenecks} \\
T_{\text{max}} & \text{else}
\end{cases} \]
Simulation results: **without** ACC exploitation
Simulation results: with ACC exploitation
Local-level tasks:

- **Urban intersection**
  - *Speed* control (reduction of stops)
  - *Eco*-driving
  - *Platoon-forming* while crossing urban intersections
    - increased saturation flow
  - *Dual vehicle* ↔ traffic signal **communication**
  - *No/virtual traffic signals*
    - Crossing sequence
    - Safe and convenient vehicle trajectories
    - Vulnerable road users
    - Mixed traffic?
Rush Hour by Fernando Livschitz
https://www.youtube.com/watch?v=MRPK1rBl_rI
Too difficult?
Individual drivers act autonomously

- **Monitor**: other arriving vehicles on higher-priority approaches
- **Communicate**: turn blinker
- **Predict**: ego and other vehicles trajectories; potential conflicts
- **Decide**: go or non-go
- **Repeat**: whole loop, if non-go decision
- **Emergency** reaction: in real time, if go decision

- Video in lapse time
Automated/Connected vehicles?

- **Monitor**: with sensors → all around, simultaneously, fast
- **Communicate**: V2V, V2I → comprehensive, fast
- **Predict**: computation based on assumptions → fast
- **Decide**: go or non-go
- **Repeat**: whole loop, if non-go decision → high frequency (real-time MPC)
- **Emergency** reaction: in real time, if go decision
- Overall fast, reliable
- Weak point: Prediction **uncertainty** (disturbances)
  - Stochasticity margins
  - Physical inertia
  → reduced efficiency for higher reliability
Local task example: bottleneck control
(for throughput maximisation)

Feedback-based

\[
\begin{align*}
\hat{y} & \rightarrow \hat{y} \\
& \downarrow K \\
\downarrow & \\
& \rightarrow u(k) \\
& \rightarrow \text{Linear feedback/feedforward law} \\
& \rightarrow \text{Traffic system} \\
& \rightarrow x(k)
\end{align*}
\]
Application Example (lane changing only)

Without Control

With Control
Link/Network-level tasks:

- Route guidance

- Urban road networks
  - **Offset** control (reduction of stops)
  - **Platoon-forming**: Stronger intersection interconnections (increased saturation flow, queues)
  - **Saturated** traffic conditions?
    - Handling?
    - Storage space? Where?
Motorway Link-level control

- Control actuators

Mainstream Traffic Flow Control (MTFC) through variable speed limits, regulating the speed of all vehicles travelling in the motorway.

Lane-changing actions, imposing some vehicles to move to a neighbouring lane.

Ramp metering (RM) actions regulating the flow entering at on-ramps.

Link control: Model-based Optimisation (case study)

Monash Freeway (M1), Melbourne, Australia (data: courtesy VicRoads)
Link control results
6. FUNCTIONAL/PHYSICAL ARCHITECTURE

Conventional TM Architecture

Various options for task share among RSC and TCC
Decentralised Vehicle-Embedded TM

- Self-organisation (e.g. bird flock or fish school)
- Single vehicle sensors: Is this sufficient information for sensible TM actions?
Decentralised Vehicle-Embedded TM

- **V2V Communication**: Extended traffic flow information
- How far ahead/behind should a vehicle be able to “see” for sensible TM?
- Where is data aggregation taking place?
- What about network-level TM? (ramp metering, route guidance)
Hierarchical TM

- **Vehicle level**: ACC, obstacle avoidance, lane keeping, …
- **V2V level**: CACC, cooperative lane-changing, cooperative merging, warning/alarms, platoon operations
- **Infrastructure level**: speed, lane changing, time-gaps, platoon size, ramp metering, route guidance
7. CONCLUSIONS

- Intelligent vehicles may lead to dumb traffic flow – if not managed appropriately
- Connect VACS and TM communities for maximum synergy
- TM remains vital while VACS are emerging

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