The Smart Highway – Modern Traffic Control

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Traffic measures

Dynamic Route Information Panel (DRIP)

Ramp metering
Traffic lights
Dynamic speed limits
Dynamic lanes

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Traffic measures

• Lights
  • Traffic lights
  • Ramp metering
• Information
  • Dynamic Route Information Panels
  • Dynamic speed limits
  • RDS-TMC
  • Travel information
• Dedicated lanes
  • Dynamic left lane
  • Emergency hard shoulder, peak lane
  • Dynamic lane marking (light emitting road marking)
• Road pricing
Traffic control – remarks

- Control loop – extremely large loop with many uncertainties
- Disturbances – have a very high impact on the traffic system (accidents, road work, bomb alarm)
- Hybrid control – combines discrete and continuous control in one scheme
- Model predictive control – takes into account multiple constraints and uses models of the system
Examples of projects

- Multi agent control
- Freeway and urban traffic control
- Traffic information and traffic control
- Shock waves
- Autonomous vehicles
Coordinated ramp metering

- Links, services, measures
- Length of the onramp
- Coordination stream up
- Hierarchical solution is limited
### Link and services agents

- Link agents observe the local traffic situation and determine local actions, they can discuss local actions with other link agents.

- Service-agents collect the demands of link agents, they decide a tactical solution for the link agents.
Four link agents without (left) and with (right) control
The onramps

velocity

density
Problems

- Long term – short term behavior with ramp metering
- Coordination of more or less independent units
- Stability
A network of freeway and urban traffic
Modeling

- Freeway: macroscopic model, based on segments
- Computes flow, density and velocity
- Urban: short time steps, queuing
Five simulation scenario’s

- Marginally saturated intersections
- Morning rush, traffic traveling into the city
- Evening rush, traffic leaving the city
- Congestion at one of the urban intersections
- Congestion on the freeway
Simulation results: Freeway I

Density

Velocity
Simulation results: Off-ramp

Free space

Flow
Simulation results: On-ramp

Queue length

Flow
Simulation results: Urban queue lengths
Model Predictive Control

- Control signal: offsets, green times
- Cost function: Total time spent

\[ TTS = T_u \times \sum \text{vehicles(urban)} + T_f \times \sum \text{vehicles(freeway)} \]

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal traffic</td>
<td>7.6%</td>
</tr>
<tr>
<td>Morning rush hour</td>
<td>6.2%</td>
</tr>
<tr>
<td>Evening rush hour</td>
<td>8.2%</td>
</tr>
<tr>
<td>Urban congestion</td>
<td>3.9%</td>
</tr>
<tr>
<td>Freeway congestion</td>
<td>6.4%</td>
</tr>
</tbody>
</table>
Model Predictive Control

- Keep traffic waiting at origins
- More green for crossing traffic
- Improve flow towards the freeways

Queue length

![Queue length graph](image)
Traffic information and traffic control
Control strategy

Minimize simultaneously:
- total time spent
- jam building at onramp
- difference between displayed and realized travel times
- variation in control signal

using
- travel time information and ramp metering
Model predictive control

Measurements

Optimal control actions

Disturbances

Prediction Model

Objectives & Constraints

Process

Disturbances

Apply Current Optimal Control to Process

$k = k+1$
Effect of the controller
Without control (left) and with MPC (right)
Deviation in travel time information with MPC **without** and **with** prediction error minimization in cost function
Results

• Cost function with prediction error minimization guarantees optimal and precise travel times
• MPC algorithm for integral control can significantly reduce the total time spent (~20%)
• Prototype traffic control system possible in MATLAB, quick implementation on the road
Shock waves
Network traffic
local vs. global

- coordination
  - blocking of other streams

- influences possible on whole route
Experimental Setup

• compare ramp-metering only with ramp metering and speed limits
• minimize TTS + small control variation penalty
Model Predictive Control

past → future

set-point $r$

predicted outputs $y$

computed manipulated variables $u$

control horizon

prediction horizon
Results

**without control**

- **time:** 24 min
- **Speed (km/h):**
- **Density (veh/km):**

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**with control**

- **time:** 11 min
- **Speed (km/h):**
- **Density (veh/km):**
Results

• Prediction horizon: 7 minutes
• Control horizon: 5 minutes
• Introduction of speed limits reduced TTS from 815 veh·h to 737 veh·h (9.6%)
• Congestion resolved in ca. 2 hours instead of 3 hours

• MPC suitable for coordinating ramp metering and speed limits
• Speed limits useful for congestion prevention/reduction
Autonomous driving

- Demo setup consisting of three vehicles with IR-communication
  - Communication up to 300m
  - Multi-hop
Overview of the closed-loop system

Vehicle Dynamics → Sensors

INS

DDGPS

Sensor fusion

Throttle command

Brake command

Shift command

Longitudinal Controller

Communication Link

x, y, v, a

x, y, v, a_i

v

a_x

a_y

x

y

θ
Design of the inner loop (1)

- Acceleration control for fast reaction
- Model-free control or control method robust to model uncertainties must be chosen
- Sliding Mode Control (SMC) with a simple model is chosen:
  - Model: \( ma + f = bu \)
  - Control output: 
    \[
    u = \frac{(\frac{-\dot{e}}{\lambda} + a_{ref})\hat{m} + \hat{f}}{\hat{b}} - \frac{k}{\hat{b}} \text{sat}\left(\frac{S}{\phi}\right)
    \]
- Two SMC controllers have been used for brake and throttle because of different dynamics
- Gearbox has been controlled by shift algorithm
**Design of the inner loop (2)**

- Brake and throttle should not be applied at the same time therefore the following switching criterion has been used:
  - \(a_{ref} - a_{res} > s_1\) switch to throttle control
  - \(a_{ref} - a_{res} < s_2\) switch to brake control
  - \(s_2 \leq a_{ref} - a_{res} \leq s_1\) do not switch

- Overview of total inner loop:
  - **\(v_{veh}, u_{thr}\)**
    - Shift algorithm
    - **Switching criterion**
      - **SMC Throttle control**
        - Throttle signal to MMS
      - **SMC Brake control**
        - Signal to brake actuator
    - **Shift signal to MMS**
Design of the outer loop

• Design of the outer loop is done in a simulation environment with ATS/CAR vehicle models developed at TNO Automotive

• Main objective: keep a headway of $d_{ref}$ to front vehicle
  • Used time headway: $h = h_0 - c\Delta v$
  • Desired headway: $d_{ref} = d_0 + h v_{veh}$
  • Additional term to achieve ‘natural’ driving behaviour:
    $$a_{MND} = \frac{-(v_2 - v_1)^2}{2(d - d_{ref} + dx)}$$
Conclusions

• Traffic control is dependent of good models
• Traffic measures can be combined, but this is risky
• Large test sites with more cities and long highways will be extremely difficult to control