Fundamentals of Traffic Operations and Control

Cell Transmission Model (CTM) and Coordinated Ramp-Metering

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Week 6
October 2017
Outline

• Traffic flow modelling
• Cell Transmission Model (CTM)
• Ramp metering
• Coordinated ramp metering
  – HERO
• Discussion

Acknowledgement: Some of the presented material was kindly provided by Prof. Markos Papageorgiou (TU Crete) and Dr. Gabriel Gomes (UC Berkeley).
Why do we need models?

- **Process analysis and understanding**
- **Planning (forecasting)**
  - Introduction of a new mode (multimode)
  - Modification/extension of infrastructure
- **Operations (control)**
  - Design of model-based control strategies
  - Estimation/prediction models
  - Testing the control performance
- **Traffic simulation**
Classification of models

- Microscopic (mainly for simulation)
  car following + lane changing

- Mesoscopic
  vehicle platoons with similar characteristics

- Network level or Macroscopic (MFD)
  macroscopic traffic flow variables (in analogy to fluid mechanics)
Microscopic modelling

Detailed vehicle trajectories following each other (similar output to real data!).
Many available micro-simulation software.
Macroscopic traffic flow models

Macroscopic traffic flow variables (in analogy to fluid-mechanics):

- traffic density $\rho(x, t)$: number of vehicles per unit length ($veh/km$)
- traffic volume $q(x, t)$: number of vehicles per time unit ($veh/h$)
- mean speed $v(x, t)$ in $km/h$
Spatial and temporal modelling

- **Discretization in space**
  \[ \Delta_i \approx 10 - 500 \text{ m} \]

- **Discretization in time**
  \[ T \approx 0.2 - 15 \text{ sec} \]
  \[ T \leq \frac{\Delta_i}{v_{max}} \]
  CFL condition!
Macroscopic variables

- **Density** $\rho_i(k)$: number of veh in cell $i$ at time $t = kT$ divided by $\Delta_i$
- **Mean speed** $v_i(k)$: speed of veh in cell $i$ at time $t = kT$
- **Flow** $q_i(k)$: number of veh exiting cell $i$ over the sample period $[kT, (k + 1)T]$

**Homogeneous conditions:** $q_i(k) = \rho_i(k)v_i(k)$
Demand and supply capacities

The flows from one cell to the other are restricted by demand capacity and supply capacity.
Calibration of FD

- On ramp
- Uphill, curvature, lane drop
- Variable speed limits (VSL)
Cell Transmission Model


Off-ramp flows are negatively affected by

- congestion because of obstructed off-ramps
- congestion because of wasted capacity
- over-aggressive ramp metering

Known inlet demands
Off-ramp split ratios
Unobstructed outlets
Partitioning into cells

- Motorway has \( N + 1 \) cells, 0, 1, ..., \( N \)
- Each cell has one on-ramp and/or off-ramp
- Upstream cell has specified inflow \( r_0(k) \)
- All on-ramps have specified inflows \( r_i(k) \) and all off-ramps have specified split ratios
CTM: Flow conservation

\[ n_i(k + 1) = n_i(k) + T \left[ q_{i-1}(k) + r_i(k) - q_i(k) - s_i(k) \right] \]

Off-ramp flows are given by split ratios

\[ s_i(k) = \beta_i(k)[s_i(k) + q_i(k)] \]
\[ s_i(k) = \frac{\beta_i(k)}{\beta_i(k)} q_i(k) \]

\[ \bar{\beta}_i(k) = 1 - \beta_i(k) \]
CTM: Inter-cell flow

The flow $q_i(k)$ is limited by:

Demand for space: $v_i \rho_i(k) - s_i(k)$

Capacity: $Q_i$

Supply of space: $w_{i+1} (\bar{\rho}_{i+1} - \rho_{i+1}(k))$

$$q_i(k) = \min \{ \beta_i(k) v_i \rho_i(k), w_{i+1} (\bar{\rho}_{i+1} - \rho_{i+1}(k)), Q_i \}$$
CTM: FD for each cell

\[ q_i(k) = \min\left\{ \bar{\beta}_i(k) v_i \rho_i(k) , w_{i+1} \left( \bar{\rho}_{i+1} - \rho_{i+1}(k) \right) , Q_i \right\} \]

- Define the critical density \( \rho_i^{cr} \)
- Triangle implies: \( Q_i = \bar{\beta}_i v_i \rho_i^{cr} = w_{i+1} \left( \rho_{i+1} - \rho_{i+1}^{cr} \right) \)
CTM: Summary

\[ q_i(k) = \min\{ \bar{\beta}_i(k)v_i\rho_i(k) , w_{i+1} (\rho_{i+1} - \rho_{i+1}(k)) , Q_i \} \]

\[ 0 \leq i \leq N - 1 \]

\[ q_N(k) = \min\{ \bar{\beta}_N(k)v_N\rho_N(k) , Q_N \} \]

\[ n_i(k + 1) = n_i(k) - T \left[ \frac{q_i(k)}{\bar{\beta}_i(k)} + q_{i-1}(k) + r_i(k) \right], \quad 1 \leq i \leq N \]

\[ n_0(k + 1) = n_0(k) - T \left[ q_0(k) + r_0(k) \right] \]
Ramp metering
Why ramp metering?

- Case 1:
Why ramp metering?

- Case 2:
When is RM virtually useless?

Exit flow problems!
Local ramp metering
Demand-Capacity / ALINEA

Demand-Capacity Strategy

FEEDFORWARD (open loop)

$q_{\text{in}}$ $O_{\text{out}}$

$\hat{r}$

$q_{\text{cap}}$

ALINEA (I-type regulator)

$r(k) = r(k-1) + K_R [\hat{\delta} - o_{\text{out}}(k)]$

$q_{\text{in}}$ $O_{\text{out}}$

$\hat{\delta}$
Amsterdam Ring Road
Coordinated ramp metering
**HERO**

**HEuristic Ramp metering coOrdination:**

- Rule-based central control
- Suitable modification of the subordinate ALINEA controller
- Real-time input: only current ramp storages $l_i(k)$
- Efficiency: close to nonlinear MPC
- MPC has computational restrictions
HERO: rule-based coordination

- Apply ALINEA to each ramp with $\hat{o} = o_{cr}$ and $l_{\text{min}}$ constraint.
- If ALINEA active at ramp $i$ (master) and $l_i > \text{threshold1}$, then set an analogous $l_{\text{min}}$ for the next upstream ramp $i-1$ (slave) (i.e. enlarge the available storage space).
- If $l_i + l_{i-1} > \text{threshold2}$, then set an analogous $l_{\text{min}}$ for the next upstream ramp $i-2$ (slave)...
- ... and so forth, up to ramp $i-M$ or encounter of another ramp cluster.
- De-activation logic (based on congestion).
HERO: rule-based coordination
HERO implementation (Australia)
Monash freeway (Australia)
AM PEAK Typical day (Fixed Time)

Bottleneck created due to large number of lane changing

THRU LANE SPEED RANGES in KM/HR

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PM PEAK Typical day (No RM)

Bottleneck created due to merge at Forster ramp
PM PEAK Typical day (HERO)

Bottleneck cleared
Discussion!

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