Integrated Local VSL and Ramp Metering Control to Mitigate Recurrent Bottlenecks

Base Model-I

2015.03.03
Outline

- Introduction
- Macroscopic Traffic flow Model
- Control Algorithms
  - Feedback Control
  - Integrated Control
- Case Study
- Advanced model
Introduction

- Local bottleneck
  - Lane drop
  - Work zone
  - Tunnels, narrow bridges, etc.

How to deal with this issue?
**Introduction**

- **Control Strategies**
  - Variable speed limits
  - Ramp metering

- How to design the control system?
- How to coordinate these two strategies?
Macroscopic Simulation Model

- Flow conservation:
  \[ \rho_i(k+1) = \rho_i(k) + \frac{\Delta T}{L_i \lambda_i} [q_{i-1}(k) - q_i(k) + r_i(k) - s_i(k)] \]

- Speed-density relationship:
  \[ V[\rho_i(k)] = v_{f,i} \exp \left[ -\frac{1}{a_i} \left( \frac{\rho_i(k)}{\rho_{cr,i}} \right)^a \right] \]

- Dynamic speed equation:
  \[ v_i(k+1) = v_i(k) + \frac{\Delta T}{\tau_i} \left[ V(\rho_i(k)) - v_i(k) \right] + \frac{\Delta T}{L_i} v_i(k) [v_{i-1}(k) - v_i(k)] - \frac{v_i \Delta T [\rho_{i+1}(k) - \rho_i(k)]}{\tau_i L_i} \frac{\rho_i(k) + \kappa_i}{\rho_i(k)} \]

- Flow equation:
  \[ q_i(k) = \rho_i(k) v_i(k) \lambda_i \]
Macroscopic Simulation Model

- Ramp queue length:
  \[ w_i(k+1) = w_i(k) + \Delta T [d_i(k) - r_i(k)] \]

- On-ramp flow rate:
  \[ 0 \leq r_i(k) = \min \{ d_i(k) + w_i(k) / \Delta T, RM(k) \} \]
  - \( d_i(k) \): on-ramp demand (veh/h)
  - \( r_i(k) \): on-ramp flow rate (veh/h)
  - \( RM(k) \): ramp metering rate (veh/h)
  - \( w_i(k) \): on-ramp queue length (veh)
Macroscopic Simulation Model

Model calibration

- $v_f, \rho_{cr}, \alpha$
  - calibrated based on the fundamental diagram
  - constructed from collected field data

- $\tau, V, K$
  - calibrated to minimize the summation of percentage differences in speed and flow rate between the model and field data

$$\text{Error} = \sum_{j=1}^{J} \sum_{k=1}^{K} \left( \frac{v_{\text{mes}}(k, j) - v_{\text{model}}(k, j)}{v_{\text{mes}}(k, j)} \right)^2 \left( \frac{q_{\text{mes}}(k, j) - q_{\text{model}}(k, j)}{q_{\text{mes}}(k, j)} \right)^2$$

- Solution method:
  - Sequential quadratic programming

- Initial starting point:
  - Latin hypercube sampling

$k$: time index

$j$: segment index
Feedback Control

Initialization
k=0, m=1

Detector Data

k=mN_R?

No

k=N_V?

No

Yes

Ramp Metering

m=m+1

k=k+1

Yes

VSL Control

k=mN_R?

Yes

Detector Data

k: time step
m: counter
N_R: control interval for ramp metering
N_V: control interval for VSL
In general, N_R<N_V
Feedback Control

Ramp metering

\[
RM_{Temp}(m+1) = RM(m) + K_r \times (o_{cr} - o_{target}(m))
\]

\[
RM(m+1) = \min(RM_{Temp}(m+1), RM_{up})
\]

\[
RM(m+1) = \max(RM_{Temp}(m+1), RM_{Low})
\]

if \( w(m) > w_{\text{max}} \)

Override the ramp metering system to prevent queue spillback

- \( o_{target}(m) \): detected average occupancy over the target segment at the \( m_{th} \) control interval
- \( o_{cr} \): critical occupancy (%)
- \( K_r \): positive constant parameter
- \( RM(m) \): ramp metering rate at the \( m_{th} \) control interval (veh/h)
- \( RM_{up} \): lower bound of the ramp metering rate (veh/h)
- \( RM_{low} \): upper bound of the ramp metering rate (veh/h)
- \( w(m) \): queue length at the \( m_{th} \) control interval (veh)
- \( w_{\text{max}} \): maximum allowed queue length (veh)
Feedback Control

- **VSL Control**

  \[ \text{if } o_{\text{target}}(t) > o_{\text{cr}} \]
  \[ VSL_{1\_Temp}(t+1) = VSL_1(t) - \Delta \]
  \[ VSL_1(t+1) = \max(VSL_{1\_Temp}(t+1), \text{Lower}) \]

  \[ \text{else } \]
  \[ VSL_{1\_Temp}(t+1) = VSL_1(t) + \Delta \]
  \[ VSL_1(t+1) = \min(VSL_{1\_Temp}(t+1), \text{Upper}) \]

  \[ \text{end } \]

  \[ VSL_0(t+1) = VSL_1(t+1) \]
  \[ VSL_2(t+1) = \min(VSL_1(t+1) + \Delta, \text{Upper}) \]
  \[ VSL_3(t+1) = \min(VSL_2(t+1) + \Delta, \text{Upper}) \]

- \( o_{\text{target}}(t) \): detected average occupancy of the target segment at the \( t \)th control interval (%)

- \( o_{\text{cr}} \): critical occupancy (%)

- \( VSL_i(t) \): Speed displayed for VSL \( i \) at the \( t \)th control interval (km/h)

- \( \Delta \): VSL speed increment (km/h)

- Lower: lower bound of the speed limit (km/h)

- Upper: upper bound of the speed limit (km/h)

- \( VSL_{\text{-1}} \): critical VSL

- \( VSL_{\text{-2,3}} \): upstream VSLs

- \( VSL_{\text{-0}} \): downstream of \( VSL_{\text{-1}} \), whose speed is always set equal to \( VSL_{\text{-1}} \), in case there is on-ramp between \( VSL_{\text{-1}} \) and the bottleneck.
Integrated Control

$k$: time step
$m$: counter
$N_R$: control interval for ramp metering
$N_V$: control interval for VSL
In general, $N_R < N_V$

1. Initialization
   $k=0$, $m=1$

2. Detector Data
   - Yes
   - No

3. Ramp metering
   - Yes
   - No
   - $k=mN_R$?

4. Traffic flow model

5. Optimization model

6. VSL Control
   - Yes
   - No
   - $k=N_V$?

7. $k=m+1$

8. $m=m+1$

9. $k=k+1$
Integrated Control

- **VSL control**
  - adjusted over $N_V$ unit intervals
  - use the same control strategy in the feedback control

- **Ramp metering**
  - Objective: minimize the proposed cost function
  - Predict the traffic conditions for the next $N_V$ intervals
  - Adjust the metering rate over every $N_R$ intervals based on the computed objective function

$N_R$: control interval for ramp metering
$N_V$: control interval for VSL
In general, $N_R < N_V$
Integrated MPC Control

- **Ramp metering**
  - **Objective function**
    - to minimize the weighted total travel time and maximize the weighted total travel distance
    - Penalize when the density of the target segment goes above the critical density
    
    $\text{Min Cost} = \alpha_{\text{TTT}} \sum_{k=k_0+1}^{k_0+N_t} \sum_{j=1}^{J} \left[ \rho_j(k) \lambda_j L_j + w_j(k) \right] - \alpha_{\text{TTD}} \sum_{k=k_0+1}^{k_0+N_t} \sum_{j=1}^{J} \rho_j(k) v_j(k) \lambda_j L_j + \delta(k_0)$

    $\delta(k_0) = \begin{cases} 
    0 & \text{if mean} \left[ \rho_{\text{target}}(k_0 + 1 : k_0 + N_r) \right] < \rho_{cr} \\
    M & \text{if mean} \left[ \rho_{\text{target}}(k_0 + 1 : k_0 + N_r) \right] \geq \rho_{cr}
    \end{cases}$

    - where, $k_0$ is the current time step, $M$ is a very large number
  - **Solution method**
    - Sequential quadratic programming
Case Study

- **Freeway No.5**
  - Length: 54 km
  - Su Ao – Nan Gang
  - Hsuehshan Tunnel
    - Length: 12.9 km
    - 28.15 km – 15.25 km
  - Network covered by Macro-Simulation
    - 32.7 km – 23.5 km

Covered area

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Traffic Safety and Operations Lab
University of Maryland, College Park
Case Study

- **Segment length**: about 500m
- **Four VSL signs, one ramp metering**
Case Study

- Why starts from 23.5 km?
  - That is where congestion starts.

- Why ends at 32.7 km?
  - Congestion tail ends before this position.
Model calibration results

25.6 km

26.3 km
Model calibration results

27.8 km

28.4 km
## Results Comparison

### Total travel time

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>No Control</th>
<th>Feedback VSL Only</th>
<th>Feedback RM Only (Ramp queue &lt; 100)</th>
<th>Feedback VSL+RM (Ramp queue &lt; 100)</th>
<th>Integrated VSL+RM (Ramp queue &lt; 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Travel Time (veh*h)</td>
<td>1326</td>
<td>1219</td>
<td>1309</td>
<td>1186</td>
<td>1168</td>
</tr>
<tr>
<td>Improvement (%)</td>
<td>N/A</td>
<td>8%</td>
<td>1%</td>
<td>10.6%</td>
<td>11.9%</td>
</tr>
</tbody>
</table>
Results Comparison

- Speed evolution: @ 25.6 km
Results Comparison

- Speed evolution: @ 26.3 km
Results Comparison

- Speed evolution: @ 27.8 km
Results Comparison

❖ Speed evolution: @ 28.4 km

<table>
<thead>
<tr>
<th></th>
<th>No Control</th>
<th>VSL only</th>
<th>RM only</th>
<th>VSL+RM FB</th>
<th>VSL+RM Opt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (km/h)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (min)</td>
<td></td>
<td></td>
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</tbody>
</table>
On-going Work

- Calibrate the VISSIM network
- Extend the control strategies to the entire freeway segment.
- Incorporate VSL compliance rates into the prediction and simulation model
Thank you.
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