Modeling and Evaluation of Adaptive Bus-Preemption Control with and without AVL Systems

Paper Outline

Introduction of adaptive bus-preemption signal control system

System component

System control logic

Illustrative example
Introduction

- Bus signal preemption is used to encourage more people to take public transit.
- Adaptive signal control is a promising method to relieve urban traffic congestion.
- This paper integrates the bus-preemption with adaptive signal control.
- Schedule delay is taken into account when optimizing the signal.
- Automated vehicle location (AVL) system is incorporated into the integrated system.
Interrelationship between system component

Detailed description for each module will be given in the following slides.
Surveillance systems

- The adaptive control system needs two types of detectors:
  1) Vehicle detectors:
     - 36.6 m (per lane) from the stop line (downstream detector)
     - 15.25 m (per lane) from the upstream section (upstream detector)
  2) Bus detectors:
     - 36.6 m (per lane) from the stop line to detect the bus arrival
     - at the stop line (per lane) to detect the bus departure
Traffic state estimation module

- Queue length estimation

\[ Q_i^l (k+1) = \max \{ Q_i^l (k) + A_i^l (k+1) - d_i^l (k+1), 0 \} \forall l \in P^i; \forall P^i \in i; \forall i \in H \]
Traffic state estimation module

- Estimation of arrivals
- First, we need to show the relation between detector placement and arrival queue estimation.

[Diagram showing upstream and downstream detectors with distance between two detectors divided into several small boxes.]

(Cruise speed = 1 box per 3 sec)
Traffic state estimation module

- Estimation of arrivals (Cont.)
  - If downstream detector is not occupied by queued vehicles
    \[ A^i_l(k) = q^i_{l,d}(k-1) \quad \text{if } Q^i_l(k) \leq D_1 \] (2)
    - Number of arrivals of lane l at time step k and phase i
    - Traffic flow of lane l, detected by downstream detector d, at time step k-1 and phase i
  - If downstream detector is occupied by queued vehicles
    \[ A^i_l(k) = a^i_{l,1}(k) \quad \text{if } D_2 \geq Q^i_l(k) \geq D_1 \] (3)
    - Number of arrivals of lane l moving in box 1 from upstream detector at time step k and phase i
    - Number of arrivals of lane l moving in box 1 from upstream detector at time step k and phase i
Traffic state estimation module

- Estimation of arrivals (Cont.)

\[
a^i_{l,1}(k) = a^i_{l,2}(k - 1) \quad (4)
\]

Number of arrivals of lane \( l \) moving in box 1 from upstream detector at time step \( k \) and phase \( i \)

\[
a^i_{l,(N-1)}(k) = a^i_{l,N}(k - 1) + (1 - F)q^i_{l,u}(k - 1) \quad (5)
\]

Number of arrivals of lane \( l \) moving in box \( N-1 \) from upstream detector at time step \( k \) and phase \( i \)

Number of arrivals of lane \( l \) moving in box \( N \) from upstream detector at time step \( k-1 \) and phase \( i \)

Traffic flow of lane \( l \), detected by upstream detector \( u \), at time step \( k-1 \) and phase \( i \)

\( F \) is a fractional number denotes the percentage of upstream flow will enter the Box \( N \).
Traffic state estimation module

- Estimation of arrivals (Cont.)

\[ a^i_{l,N}(k) = F q^i_{l,u}(k - 1) \]  (6)

- Number of arrivals of lane \( l \) moving in box \( N \) from upstream detector at time step \( k \) and phase \( i \)
- Traffic flow of lane \( l \), detected by upstream detector \( u \), at time step \( k-1 \) and phase \( i \)

\( F \) is a fractional number denotes the percentage of upstream flow will enter the Box \( N \).
Traffic state estimation module

- **Estimation of discharged flow**

\[ d_i^i(k) = T \left[ 1 - \phi^i(k) \right] \left\{ S_{l,g}^i \left[ 1 - \xi^i(k) \right] + S_{l,y}^i \xi^i(k) \right\} + TS_{l,g}^i \xi^i(k) \phi^i(k) \] (7)

- Discharge flow rate is equal to saturation flow rate for green time, saturation flow rate for yellow time or zero.

- If it is green phase and not switch: \( \phi^i(k) = 0, \xi^i(k) = 0, d_i^i(k) = TS_{l,g}^i \)
- If it is green phase and switch: \( \phi^i(k) = 0, \xi^i(k) = 1, d_i^i(k) = TS_{l,y}^i \)
- If it is red phase and switch: \( \phi^i(k) = 1, \xi^i(k) = 1, d_i^i(k) = TS_{l,g}^i \)
- If it is red phase and not switch: \( \phi^i(k) = 1, \xi^i(k) = 0, d_i^i(k) = 0 \)
Signal state computation

- Signal state

\[ \phi^i(k) = \xi^i(k-1) + \phi^i(k-1) - 2\xi^i(k-1)\phi^i(k-1) \quad (8) \]

Signal state at time step \( k \) and phase \( i \),
0 -- green
1 -- red

1 -- if signal state is switched at the end of time step \( k-1 \)
0 -- otherwise

\[ \text{If } \phi^i(k-1) = 0, \xi^i(k-1) = 0, \quad \phi^i(k) = 0 \]
\[ \text{If } \phi^i(k-1) = 0, \xi^i(k-1) = 1, \quad \phi^i(k) = 1 \]
\[ \text{If } \phi^i(k-1) = 1, \xi^i(k-1) = 0, \quad \phi^i(k) = 1 \]
\[ \text{If } \phi^i(k-1) = 1, \xi^i(k-1) = 1, \quad \phi^i(k) = 0 \]
Signal state computation

- **Elapsed green**
  \[ U^i(k) = \left[ U^i(k-1) + T \right] \left[ 1 - \xi^i(k-1) \right] \] (9)

  - Green time used by phase i at the end of time step k
  - 1 -- if signal state is switched at the end of time step k-1
  - 0 -- otherwise

- Green time is either increased by a duration T or reduced to zero.
Signal state computation

- **Minimum green**

\[
G_{min}^i = t_{sd}^p + \left( \max \left\{ \left( \frac{D_1}{L_v + S_d} + 1 \right), \frac{\text{avg} \ Q_l^i(k)}{q_s^l} \right\} \right) \left( \frac{3600}{q_s^l} \right)
\]

- **Minimum Green time** is provided for drivers to safely react to the signal change and should also be sufficiently long to discharge the average waiting queue.

- Minimum green time for phase i
- Starting delay for passenger car
- Number of vehicles will occupy the length D1
- Average queue length of all lanes in phase i at time step k
- Given saturation flow rate for lane l
Signal state computation

- Maximum green
- A sufficiently long green could be set so that the control algorithm can handle the oversaturated condition.
Performance function for bus-preemption

- In a multi-phase control intersection

\[ PI = \sum_{i' \in H} PI^{i'} \]

- Performance Index (PI) value is the sum of \( PI^{i'} \) for each competing phase \( i' \) of phase \( i \).

- For each competing phase \( i' \):

\[ PI^{i'} = c_p C_{pd}^{i'} + c_v C_{vd}^{i'} + c_{bs} C_{sd}^{i'} \]

Trade off in passenger delay

Trade off in vehicle delay

Trade off in bus schedule delay
Performance function for bus-preemption

- Computing the trade-off in passenger delay:

\[ C_{pd}^{i'} = R^{i'}(k) \sum_{\forall l} \left[ n_p \sum_{l, j=1}^{B^i_j(k)} P_{l,j}^i(k) \right] \]

\[-T \sum_{\forall l} \left[ n_p \sum_{l, j=1}^{B^i_j'(k)} P_{l,j}^{i'}(k) \right] \]

- First term denotes the total passenger delay for vehicles in phase i if green of phase i is terminated.
- Second term denotes the total passenger delay for vehicles in phase i' if green of phase i is extended.
Computing the trade-off in passenger delay (Cont.):

\[
C_{pd}^{i'} = R^{i'}(k) \sum_{\forall l} \left[ \sum_{j=1}^{B_l^i(k)} n_p PQ_l^i(k) + \sum_{j=1}^{B_l'^i(k)} P_{j,l}^i(k) \right] \\
- T \sum_{\forall l} \left[ \sum_{j=1}^{B_l'^i(k)} n_p PQ_l'^i(k) + \sum_{j=1}^{B_l'^i(k)} P_{j,l}^i(k) \right]
\]

PQ\(_l^i(k)\): Estimated passenger queue length of lane \(l\) at time step \(k\) for phase \(i\)

\(n_p\): Average number of passengers in passenger car

\(B_l^i(k)\): Number of detected buses of lane \(l\) at time step \(k\) for phase \(i\)

\(P_{j,l}^i(k)\): Number of passenger in bus \(j\) of lane \(l\) at time step \(k\) for phase \(i\)

\(R^{i'}(k) = Y^i + AR^i + G_{\text{min}}^{i'}\)

(The minimum waiting time for phase \(i\) if green is switched over equals to the sum of yellow time, all red time and minimum green for phase \(i\).)
Performance function for bus-preemption

Computing the trade-off in vehicle delay:

\[ C_{vd}^{i'} = \left[ t_{sd}^p \sum_{\forall l} PQ_l^i(k) + t_{sd}^b \sum_{\forall l} B_l^i(k) \right] - \left[ t_{sd}^p \sum_{\forall l} PQ_l^{i'}(k) + t_{sd}^b \sum_{\forall l} B_l^{i'}(k) \right] \]

- First term denotes the vehicle starting delay for vehicles in phase \( i \) if green of phase \( i \) is terminated.
- Second term denotes the vehicle starting delay for vehicles in phase \( i' \) if green of phase \( i \) is extended.

\( t_{sd}^p \) : starting delay for passenger car
\( t_{sd}^b \) : starting delay for bus
Performance function for bus-preemption

- Computing the trade-off in schedule delay:

\[ C_{sd}^{i'} = \sum_{\forall l} \sum_{\forall j} D_{j,l}^{i}(k) - \sum_{\forall l} \sum_{\forall j} D_{j,l}^{i'}(k) \]

- First term denotes the bus schedule delay for buses in phase \( i \) if green of phase \( i \) is terminated.
- Second term denotes the bus schedule delay for buses in phase \( i' \) if green of phase \( i \) is extended.
Performance function for bus-preemption

- Computing the trade-off in schedule delay (Cont.):

\[ D_{j,l}^i(k) = R^i(k) + t_{sd}^b + \left[ F_{j,l}^i(k) - d_{l}^i(k) + 1 \right] \frac{3600}{q_s^l} + SD_{j,l}^i(k-1) \]

Total delay for bus j, in lane l and phase i, if green is terminated at the end of step k

Minimun waiting time for the next green

Bus starting delay

Number of vehicles detected ahead of bus j, in lane l, at step k and phase i

Discharge vehicles of lane l at step k and phase i

Given saturation flow rate for lane l

Schedule delay for bus j of lane l at step k-1 and phase i

\[ D_{j,l}^{i'}(k) = T + t_{sd}^b + \left[ F_{j,l}^{i'}(k) - d_{l}^{i'}(k) + 1 \right] \frac{3600}{q_s^l} + SD_{j,l}^{i'}(k-1) \]

Total delay for bus j, in lane l and phase i’, if green is extended at the end of step k

It should be pointed out that without AVL system, the bus schedule delay is not possible to obtain and assumed to follow a distribution.
Automatic vehicle location (AVL) system

- Information from AVL system
  - No. of buses in the link
  - Location of a bus in the link
  - No. of passengers in a bus
  - Schedule delay of a bus
  - Speed of a bus

- Bus queue length computation module
  - With the above information, AVL can provide the number of buses in the queue.
  - AVL can also include buses beyond the queue length but will join the queue in one control time step into the PI calculation.
System control logic (Flowchart)

Detailed step by step description will be provided in the next slide.
System control logic

- **Step 1:**
  - At step $k$ and phase $i$, compute the minimum and maximum green time.

- **Step 2:**
  - Check whether the min and max green is violated.
    - 1) If current green time is less than the minimum, extend the green.
    - 2) If green already used is greater than maximum, terminate the green immediately.
    - 3) If both conditions are satisfied, go to step 3

- **Step 3:**
  - Examine whether there is bus competing for preemption
    - 1) If there is not, set $B_{i}^{j}(k)$ and $P_{j,i}^{i}(k)$ to zero.
    - 2) If there is and without AVL, system provides the bus presence information through the 36.6 m bus detector.
    - 3) If there is and with AVL, system can provide the information for queued bus and the buses will join the queue.
System control logic (Cont.)

- Step 4:
  - Calculate the net benefit of extending the green with the proposed PI function

- Step 5:
  - If PI is negative, it means that the current decision is not favorable and a switchover decision is taken.
  - If PI is positive, extend the green for another T seconds. (T=3)
Illustrative example

- **Layout:**

- Two phase control.
- Traffic volume varies as 300, 500 and 1000 vphpl.
- Headway of buses is 180 sec (20 buses/h) and 120 sec (30 buses/h).
- Two bus route for NS approaches and one each for EW approaches.
Illustrative example

- Results (Without AVL):
- Without preemption VS with preemption

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<th>Traffic volume (vphpl)</th>
<th>Mean bus discharge headway (sec)</th>
<th>Delay for model without preemption (sec)</th>
<th>Delay for model with preemption (sec)</th>
<th>% Increase in delay for model without preemption</th>
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</table>
Illustrative example

- Results (Without AVL):
- Without preemption VS with preemption

300 vphp1, 180 sec bus

1000 vphp1, 120 sec bus
Illustrative example

- Results (With AVL):
- Without preemption VS with preemption

<table>
<thead>
<tr>
<th>Traffic volume (vph/pl)</th>
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<th>Delay for model without preemption (sec)</th>
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</table>
Illustrative example

- Results (With AVL):
  - Without preemption VS with preemption

300 vphpl, 180 sec bus
500 vphpl, 120 sec bus
Illustrative example

Results (With AVL):

- Without preemption VS with preemption

1000 vphpl, 180 sec bus
Thank You!

Questions and Comments?

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