Research Update

Bus Speed Control System

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INTRODUCTION

❖ BUS Bunching

<Scheduled timetable>  <Traffic Delay>  <Unbalanced PAX Demand>  <Traffic Signal Inference>
INTRODUCTION

❖ Stop-and-go Driving

Source: "Traffic Congestion and Greenhouse Gases" by Matthew Barth and Kanok Boriboonsomsin (Access, number 35, Fall 2009)
INTRODUCTION

- **Objective**
  - Develop a bus speed control system so as to minimize bus headway variance while reducing the fuel consumption

- **Decision Outcome**
  - Advisory bus speed to the next traffic signal
Bus Speed Control Environment

- **Bus Speed Control Condition:**
  - Frequent bus service
  - Far-side bus stops
  - Pre-timed signal control

- **Given Information:**
  - Individual bus information
  - Traffic information
  - Signal information
Assumptions

- **Travel speeds** of general traffic between stops and passenger **arrival rates** at each stop are assumed known and fixed for the period of interest.
- **Signal timing plans** for each intersection between stops are **pre-timed and fixed** for the period of interest.
- Each stop has a **dwell time function depending on the number of passengers boarding**.
- **Buses obey advisory running speed**.
- **Vehicles at intersections are fully discharged** in every cycle.
- **Bus stops are located in the far-side.**
Rolling Horizon Approach

- Whenever a bus(k) arrives at the bus stop(n), the system provides the adjusted speed to the next stop so as to reduce headway variance up to the bus stop(n+m) that the preceding bus(k-1) just left in a way to improve fuel efficiency.

\[ ta_{k,n} \]
\[ ta'_{k,n+1} \]
\[ ta'_{k-1,n+1} \]
\[ ta'_{k,n+m} \]
\[ ta'_{k-1,n+m} \]

- Actual arrival time of bus k at stop n
- Estimated arrival time of bus k at stop n
Bi-Level bus speed control:

1. Determine how many cycles the bus waits to pass the n\textsuperscript{th} signal so as to reduce headway variance

2. Determine a bus advisory speed to enhance fuel efficiency with the reduced signal stopped delay
Notation

• k: bus index, k=1,…,K
• n: bus stop index, n=1,…,N
• i: driving mode index (i=1:stop, 2: cruise, and 3:acceleration)
• e_k: stop immediately upstream from bus k, if bus k is in stop n then e_k =n
• α: weight factor included in the objective function
• t_{akn}: actual arrival time of bus k at stop n
• t_{akn}': estimated arrival time of bus k at stop n
• t_{akn}^{\hat{}}: expected arrival time of bus k at stop n
• o_n: offset of the signal between stops n and n+1
• m: previous cycle index at the current time (current cycle index: m+1)
• C: cycle length (seconds)
• τ_n: travel time from the signal to stop n+1 (seconds)
• f'_{kn}: estimated dwell time of bus k at stop n (seconds)
• b'_{kn}: estimated number of passengers who board bus k at stop n
• t_b: passenger boarding time (seconds per passenger)
• t_o: door opening/closing time (seconds)
• v_n: traffic speed between stop n and n+1
• λ_n: vehicle arrival rate at the signal between stops n and n+1 (vehicles per hour)
• Pλ_n: passenger arrival rate at stop n(passengers per minute)
Notation

- $E$: total fuel consumption (liter)
- $FR_i$: fuel consumption rate (liter per second) of driving mode $i$
- $TVSP_i$: trip time spend in driving mode $i$ (seconds)
- $VSP_i$: vehicle specific power in driving mode $i$ ($m^2/s^3$)
- $a$: acceleration rate ($m/s^2$)
- $sd_{kn}$: signal delay of bus $k$ at the signal between stops $n$ and $n+1$ (seconds)
- $d_n$: distance between stops $n$ and $n+1$ (mile)
- $ds_n$: distance between stop $n$ and the traffic signal (mile)
- $s$: saturation flow rate (vehicle per hour)
- $tr_{kn}$: start time of targeting cycle of bus $k$ at the traffic signal between stops $n$ and $n+1$
- $R_n$: red interval of the traffic signal between stops $n$ and $n+1$
- $g_n$: green time ratio of $n$th signal
- $v_{kn}^{LB}$: lower bound of bus advisory speed (mile per hour)
- $v_{kn}^{UB}$: upper bound of bus advisory speed (mile per hour)
- $t0$: estimated departure time
- $t1$: start time of target cycle
- $t2$: time that all queue is discharged
- $t3$: end time of target cycle
- $u$: unit conversion factor
- $L$: vehicle length (mile)
- $v_{kn}$: advisory bus speed (mile per hour)
Upper Level

- Determine how many cycles the bus waits to pass the nth signal so as to reduce headway difference

\[
Min \sum_{n=e_k+1}^{e_{k-1}} \alpha * (t_{a_{k-1n}} - t'_{kn})^2 + (1 - \alpha) * (\hat{t}_{a_{kn}} - t'_{kn})^2
\]

Objective

- Estimated arrival time of bus k at stop \(n+1\)
- \(t'_{kn+1} = o_n + (m + x_{kn}) * C + \tau_n - g(*)\)
- \(t'_{kn} + f'_{kn} + \frac{ds_n}{v_n} \leq o_n + (m + x_{kn}) * C\)
- \(o_n + (m + x_{kn} + 1) * C \leq t'_{kn} + f'_{kn} + \frac{ds_n}{v_n}\)
- \(f'_{kn} = b'_{kn} \cdot t_b + t_0\)
- \(b'_{kn} = P\lambda_n \cdot (t_{a_{kn}} - t_{a_{k-1n}})\)
- \(1 \leq x_{kn} \leq M\)
- \(x_{kn} \geq 0, \text{ integer}\)

Decision Variable

- How many cycles the bus k waits to pass the nth signal
• Determine how many cycles the bus waits to pass the nth signal so as to reduce headway difference
Lower Level

- Determine the bus desired speed so as to minimize the fuel consumption while satisfying the upper level decision

**Objective**

\[ \text{Min } E \]

**Decision Variable**

\[ \gamma_{kn} \geq 0, \text{ integer} \]

\[ v_{kn} = 5 \gamma_{kn} \]

\[ v_{kn}^{LB} \leq v_{kn} \leq v_{kn}^{UB} \]

\[ v_{kn}^{UB} = \begin{cases} \min \left\{ \frac{d_{sn}}{t_1 - t_0}, v_n \right\} & t_1 - t_0 > 0 \\ v_n & t_1 - t_0 \leq 0 \end{cases} \]

\[ v_{kn}^{LB} = \frac{d_{sn}}{t_1 + C - t_0} \]
Lower Level

Bus stop

Current cycle

Target Cycle

General Speed

v = \frac{ds}{T1}

T1 = t1 - t0

\begin{align*}
\text{Estimated Departure time} & : t0 \\
\text{Start time of target cycle} & : t1 \\
\text{Time that all queue discharged} & : t2 \\
\text{End time of target cycle} & : t3
\end{align*}

\begin{align*}
v1 & = \frac{ds}{T1} \\
v2 & = \frac{ds}{T2} \\
v_{UB} & = \min(v, v1) \\
v_{LB} & = v2
\end{align*}
Lower Level

Fuel consumption rate (l/s) for driving mode $i$

\[ E = \sum_{i=1}^{3} FR_i \times TVSP_i \]

For $i=1$: stop, $2$: cruise, and $3$: acceleration

Trip time spend(s) in driving mode $i$

\[ VSP_i = \begin{cases} 
0 & i = 1 \\
(v_{kn} \times u) \times 0.092 + 0.00021 \times (v_{kn} \times u)^3 & i = 2 \\
(v_{kn} \times u) \times (a + 0.092) + 0.00021 \times (v_{kn} \times u)^3 & i = 3 
\end{cases} \]

Trip time spend in driving mode $i$

\[ TVSP_i = \begin{cases} 
sd_{kn} & i = 1 \\
\frac{d_n}{v_{kn}} & i = 2 \\
\frac{v_{kn}}{a} & i = 3 
\end{cases} \]
VSP = v \times (a + g \times \sin(\varphi) + 0.092) + 0.00021 \times v^3

where VSP is the Vehicle Specific Power (m²/s³); v is instantaneous speed at which the vehicle is traveling (m/s); a is instantaneous acceleration of the vehicle (m/s²); \varphi is instantaneous road grade (decimal fraction); 0.092 is rolling resistance term coefficient; and 0.00021 is the drag term coefficient.

<table>
<thead>
<tr>
<th>VSP mode</th>
<th>VSP range (m²/s³)</th>
<th>VSP mode</th>
<th>VSP range (m²/s³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VSP ≤ 0</td>
<td>5</td>
<td>6 ≤ VSP &lt; 8</td>
</tr>
<tr>
<td>2</td>
<td>0 &lt; VSP &lt; 2</td>
<td>6</td>
<td>8 ≤ VSP &lt; 10</td>
</tr>
<tr>
<td>3</td>
<td>2 ≤ VSP &lt; 4</td>
<td>7</td>
<td>10 ≤ VSP &lt; 13</td>
</tr>
<tr>
<td>4</td>
<td>4 ≤ VSP &lt; 6</td>
<td>8</td>
<td>VSP ≥ 13</td>
</tr>
</tbody>
</table>

Lower Level

Signal delay:

\[ sd_{kn} = \begin{cases} 
0 & v_{kn} < v3 \\
[tr_{kn} + R_n - t_{kn}'] + [(t_{kn}' - tr_{kn}) \cdot \lambda_n \cdot \frac{1}{s}] & v_{kn} > v3 
\end{cases} \]

Waiting time to GREEN start:

\[ ds_n = \begin{cases} 
(t_{kn}' - (ta_{kn} + f'_{kn}))/3600 \cdot v_{kn} & v_{kn} < v3 \\
(t_{kn}' - (ta_{kn} + f'_{kn}))/3600 \cdot v_{kn} + (t_{kn}' - tr_{kn})/3600 \cdot \lambda_n \cdot L & v_{kn} > v3 
\end{cases} \]

Queue discharging Time:

boarding time + door open/close time:

\[ f'_{kn} = b'_{kn} \cdot \tau_b + \tau_0 \]

Travel distance of the bus:

\[ ds_n = \begin{cases} 
(t_{kn}' - (ta_{kn} + f'_{kn}))/3600 \cdot v_{kn} & v_{kn} < v3 \\
(t_{kn}' - (ta_{kn} + f'_{kn}))/3600 \cdot v_{kn} + (t_{kn}' - tr_{kn})/3600 \cdot \lambda_n \cdot L & v_{kn} > v3 
\end{cases} \]

Queue length:

\[ f'_{kn} = b'_{kn} \cdot \tau_b + \tau_0 \]

PAX arrival rate * bus headway:

\[ b'_{kn} = P \lambda_n \cdot (ta_{kn}' - ta_{k-1n}) \]
Numerical Example

- **Bus speed control in VISSIM**
  - Detect a bus
  - Estimate the departure time (dwell time)
  - Control bus running speed until passing the signal

*Link detector*

*Intersection detector*
Numerical Example

- 5 Bus stops
- 6 Buses with 10 min headway
- Pre-timed signal control

Signal 1
- Cycle length: 100s
- Green time: 53s
- Offset: 0s

Stop 3
- 2 PAX per min
- Boarding time: 2s per person
- Door open/closing time: 2s

$d = 0.3$ mile
$V = 30$ mph
Numerical Example
Numerical Example

- **Average Headway Difference of buses**

![Bar chart showing the average headway difference for different bus stops. The chart compares base (no control) and speed control scenarios. The reliability of bus service is improved with speed control.](chart.png)
Numerical Example

- PAX Waiting Time for a bus at each bus stop

  - Mean(s)
  - Standard Deviation(s)

Reliability of bus service is improved
### Numerical Example

#### Operation Time, #of stops, fuel consumption and emission for each bus

<table>
<thead>
<tr>
<th></th>
<th>Travel Time(s)</th>
<th>Stopped Time (s)*</th>
<th>Fuel Con. (ml)**</th>
<th>CO2(g) ***</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wo</td>
<td>W</td>
<td>Wo</td>
<td>W</td>
</tr>
<tr>
<td><strong>Bus 1</strong></td>
<td>664</td>
<td>704</td>
<td>345(88)</td>
<td>267(0)</td>
</tr>
<tr>
<td><strong>Bus 2</strong></td>
<td>553</td>
<td>757</td>
<td>247(38)</td>
<td>264(33)</td>
</tr>
<tr>
<td><strong>Bus 3</strong></td>
<td>656</td>
<td>661</td>
<td>334(99)</td>
<td>205(0)</td>
</tr>
<tr>
<td><strong>Bus 4</strong></td>
<td>665</td>
<td>701</td>
<td>342(111)</td>
<td>233(0)</td>
</tr>
<tr>
<td><strong>Bus 5</strong></td>
<td>526</td>
<td>685</td>
<td>237(66)</td>
<td>207(0)</td>
</tr>
<tr>
<td><strong>Bus 6</strong></td>
<td>648</td>
<td>676</td>
<td>331(88)</td>
<td>205(0)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3712</td>
<td>4184</td>
<td>1836(402)</td>
<td>1381(33)</td>
</tr>
</tbody>
</table>

* Stopped time is the sum of dwell time at stops and stopped time at signals. The number in parenthesis represents the sum of stopped time at signals.

*Bus operates in an environmentally-friendly way.*
On-going Work

**Model Improvement**
- Dwell-Time Estimation
- Maximum Queue Estimation

**Different Simulation Scenarios**
- Bus Service Frequency
- Congestion Level