Research Update

Bus Speed Control System

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INTRODUCTION

Objective

- Develop a bus speed control system so as to minimize bus headway variance

Decision Outcome

- Advisory bus speed to the next bus stop
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 an **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.
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 \textit{up to the bus stop(n+m) that the preceding bus(k-1) just left} in a way to improve fuel efficiency.

- $t_{ak,n}$: Actual arrival time of bus k at stop n
- $t'_{ak,n+1}$: Estimated arrival time of bus k at stop n
- $t_{a_{k-1,n+1}}$: Actual arrival time of preceding bus just left
- $t'_{a_{k-1,n+m}}$: Estimated arrival time of preceding bus just left
Bi-Level bus speed control:

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

2. Determine a bus advisory speed to enhance fuel efficiency with the reduced signal stopped delay
k: bus index, k=1,…,K
n: bus stop index, n=1,…,N
i: driving mode index (i=1:stop, 2: cruise, and 3:accelation)
e_k: stop immediately upstream from bus k, if bus k is in stop n then e_k=n
ta_{kn}: actual arrival time of bus k at stop n
ta'_{kn}: estimated arrival time of bus k at stop n
t_{kn}': estimated arrival time of bus k at traffic signal between stops n and n+1
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_0: 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

**Objective**

\[
\text{Min} \sum_{n=e_k+1}^{e_{k-1}} (ta_{k-1n} - ta'_{kn})^2
\]

\[
ta'_{kn+1} = ta'_{kn} + f'_{kn} + \frac{ds_n}{v_n}
\]

\[
ta'_{kn+1} = o_n + (m + x_{kn}) \times C + \tau_n - g(*)
\]

\[
o_n + (m + x_{kn}) \times C \leq ta'_{kn} + f'_{kn} + \frac{ds_n}{v_n}
\]

\[
ta'_{kn} + f'_{kn} + \frac{ds_n}{v_n} \leq o_n + (m + x_{kn} + 1) \times C
\]

\[
f'_{kn} = b'_{kn} \times t_b + t_0
\]

\[
b'_{kn} = \rho \lambda_n \times (ta'_{kn} - ta_{k-1n})
\]

\[
1 \leq x_{kn} \leq M
\]

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

**Decision Variable**

*How many cycles the bus \(k\) waits to pass the nth signal*
Upper Level

- 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**

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

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

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

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

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

**Desired Speed of bus k to the nth intersection**

**Desired Speed range**
Lower Level

\[ v_1 = \frac{ds}{T_1} \]
\[ T_1 = t_1 - t_0 \]
\[ v_2 = \frac{ds}{T_2} \]
\[ T_2 = t_3 - t_0 \]

\[ v_{UB} = \min(v, v_1) \]
\[ v_{LB} = v_2 \]

**Upper bound**

**Lower bound**

- **Estimated Departure time**
- **Start time of target cycle**
- **Time that all queue discharged**
- **End time of target cycle**
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 \leq 0</td>
<td>5</td>
<td>6 \leq VSP &lt; 8</td>
</tr>
<tr>
<td>2</td>
<td>0 &lt; VSP &lt; 2</td>
<td>6</td>
<td>8 \leq VSP &lt; 10</td>
</tr>
<tr>
<td>3</td>
<td>2 \leq VSP &lt; 4</td>
<td>7</td>
<td>10 \leq VSP &lt; 13</td>
</tr>
<tr>
<td>4</td>
<td>4 \leq VSP &lt; 6</td>
<td>8</td>
<td>VSP \geq 13</td>
</tr>
</tbody>
</table>

Lower Level

\[ sd_{kn} = \begin{cases} 0 & v_{kn} < v_3 \\ [tr_{kn} + R_n - t_{kn}'] + \left[ (t_{kn}' - tr_{kn}) \cdot \lambda_n \cdot \frac{1}{s} \right] & v_{kn} > v_3 \end{cases} \]

Signal delay

\[ ds_n = \begin{cases} \frac{(t_{kn}' - (ta_{kn} + f'_{kn}))}{3600 \cdot v_{kn}} & v_{kn} < v_3 \\ \frac{(t_{kn}' - (ta_{kn} + f'_{kn}))}{3600 \cdot v_{kn}} + \frac{(t_{kn}' - tr_{kn})}{3600 \cdot \lambda_n \cdot L} & v_{kn} > v_3 \end{cases} \]

Distance to the intersection

Waiting time to GREEN start

Queue discharging Time

Travel distance of the bus

Queue length

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

boarding time + door open/close time

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

PAX arrival rate * bus headway

Estimated dwell time of bus k at stop n

Estimated # of pax boarding bus k at stop n
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*
Preliminary Analysis

❖ Simulation Environment

- A segment of MD 586 WB from Randolph Rd. to Twinbrook Pkwy (3.3 mile)
- 10 bus stops and 6 traffic signals
- AM peak, Headway of 7 min, v/C of about 0.5

• Source of Signal Phase plan, Traffic count, Traffic pattern: I-TMS, MSHA
• Source of Transit information: Washington Metropolitan Area Transit Authority
Preliminary Analysis

- Average Headway at each bus stop & Standard deviation of headway at each bus stop
  - Mean(s)
  - Standard Deviation(s)
Preliminary Analysis

- **PAX Waiting Time for a bus at each bus stop**
  - Mean(s)
  - Standard Deviation(s)

**Graphs**
- Average PAX Waiting time at stops(s)
- STD of PAX waiting time at bus stop(s)
Preliminary Analysis

- **Sensitivity Analysis**
  - Bus service frequency
    - 5, 7, and 10 mins
  - Traffic Condition
    - 0, +10%, and +20%
Preliminary Analysis

- Mean and Std. of Headways of Buses by Headway

![Graphs showing average and standard deviation of headways at different bus stops for uncontrolled and controlled conditions for different headway intervals: <5min>, <7min>, and <10min>.](image-url)
Preliminary Analysis

- Mean and Std. of average PAX Waiting time by Headway

- Average PAX Waiting time at stops (s)

- STD of PAX waiting time at bus stop(s)

<5min>

<7min>

<10min>
Preliminary Analysis

Mean and Std. of Headways of Buses by Traffic Volume

- <0% (base, v/c=0.5)
- <+10%
- <+20%
Preliminary Analysis

- Mean and Std. of average PAX Waiting time by Traffic Volume

![Graphs showing average PAX waiting time and std. for different traffic volumes.](image)