Signal Timing Optimization for Improved Mobility and Air Quality

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T3e Webinar, ITS PCB Program
The Volpe National Transportation Systems Center

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Sustainable Multimodal Transportation Systems

Modeling Demand & Supply
- Mode Choice Modeling
- Traffic Flow Theory
- Simulation

Design & Management of Multimodal Systems
- Bicycle Infrastructure
- Innovative Intersection Designs
- Traffic Signal Control

Performance Measures
- Safety
- Environment
- Equity
- Public Health
- Person Mobility
Farnoush Khalighi, Transportation Modeler, Aimsun, Inc.

- **Research Interests:**
  - Traffic operations and control
  - Sustainable traffic management
  - Intelligent transportation systems
  - Environmental impacts of transportation

- **Dissertation title:**
  Signal Control and Design for Improved Person Mobility and Air Quality in Urban Multimodal Transportation Systems

- **Honors/Awards:**
  - Claire Barrett Memorial Scholarship, WTS Boston, 2015
  - 2nd position for best poster at the 16th Annual UMass Technical Day & Student Research Symposium, 2015
The UMass Amherst Transportation Engineering Program

- 7 research active faculty in transportation engineering
  - Traffic operations and control
  - Public transportation
  - Systems analysis
  - Transportation safety
  - Human factors
  - Air traffic modeling and control
  - Asset Management

- Variety of courses that include elements of ITS
  - Intelligent Transportation Systems
  - Public Transportation Systems
  - Transportation Sustainability
  - Traffic Flow Theory and Simulation I & II
University of Massachusetts Transportation Center, UMTC

**Focus**
To Improve Transportation Mobility & Safety using Innovative Technologies and Strategies
Motivation

- Growing traffic congestion
- High levels of transportation-related air pollutants
- Limited budget and infrastructure

Source: journalstar.com
Source: fiafoundation.org
Research Question

How should a signal control system be designed to balance the operational and environmental performance of signalized intersections?
Multi-objective signal control strategies:

- Operational objectives: capacity, vehicle delay, number of stops, queue length, safety [Zeng et al. (2010), Chen et al. (2011), Stevanovic et al. (2013)]
- Environmental objectives: fuel consumption, emissions or risk of human exposure to emissions [Li et al. (2004), Zhang et al. (2013), Stevanovic et al. (2015)]

Gaps:

- Only accounting for emissions of passenger cars
- Emission estimation mostly based on average speed and number of stops
- Fixed-time signal control
- Not accounting for person delay
Research Objective

- Develop a real-time bi-objective signal control system that minimizes a weighted combination of vehicle delay (or person delay) and emissions of auto and transit vehicles

- Present and provide insights into the trade-off between delay and emissions
Methodology: Assumptions

- Undersaturated traffic conditions
- Fixed cycle length, phase sequence, and yellow times
- Fixed and known capacity for each approach
- Mixed-use lanes for auto and transit vehicles
- Constant acceleration/deceleration rates
Methodology: Mathematical Model

Objective function:

\[
\text{Min } \lambda_d \left[ \sum_{j=1}^{J} (D_{j,T} + \hat{D}_{j,T+1}) + \sum_{b=1}^{b_{\text{max}}} d_{b,T} \right] + \lambda_e \left[ \sum_{j=1}^{J} (E_{j,T} + \hat{E}_{j,T+1}) + \sum_{b=1}^{b_{\text{max}}} e_{b,T} \right]
\]

- \( \lambda_d/\lambda_e \): weight of delay/emissions in the objective function (\( \lambda_d + \lambda_e = 1 \))
- \( D_{j,T}/E_{j,T} \): total auto delay/emissions of lane group \( j \) and cycle \( T \)
- \( \hat{D}_{j,T+1}/\hat{E}_{j,T+1} \): total auto delay/emissions of lane group \( j \) and cycle \( T+1 \)
- \( d_{b,T}/e_{b,T} \): delay/emissions of bus \( b \) in cycle \( T \)
- \( b_{\text{max}} \): number of buses in the optimization of cycle \( T \)
- \( J \): number of lane groups at the intersection
Methodology: Mathematical Model

Constraints:

- constant cycle length: \[ \sum_{i=1}^{I} g_{i,T} + \sum_{i=1}^{I} y_{i} = C \]
- minimum green time for each phase: \[ g_{i,T} \geq g_{i,min} \quad \forall i \in I \]
- maximum green time for each phase: \[ g_{i,T} \leq g_{i,max} \quad \forall i \in I \]
- minimum green time for each lane group: \[ G_{j}^{e}(g_{i,T}) \geq \frac{q_{j}}{s_{j}} C \quad \forall j \in J \]

C: cycle length
\( g_{i,T} \): green time of phase \( i \) in cycle \( T \)
\( y_{i} \): yellow time of phase \( i \)
\( g_{i,min} / g_{i,max} \): minimum/maximum duration of phase \( I \)
\( I \): number of phases
Methodology: Delay and Operation Times

\[ N_{j,T}^q, N_{*,a}^j, \bar{N}_{j,T}^a, t_a, q_j, D_{j,T}, t_{*,a}^{j,T}, t_q^{j,T}, s_j, \bar{D}_{j,T+1} \]

Phases \( \tau_{j,T-1} \)

Cumulative Number of Vehicles

Time

Design Cycle, \( T \)

\( C \)

\( T-1 \)

\( T+1 \)
Methodology: Delay and Operation Times

Phases

$\tau_{j,T-1}$

$\tau_{j,T}$

$N_{j,T}^q$

$N_{j,T}^{*,b}$

Cumulative Number of Vehicles

Time

$T-1$

Design Cycle, $T$

$T+1$

Methodology: Delay and Operation Times
Methodology: Driving Cycle
Methodology: Auto Emission Rates

Emission rate estimation for gasoline cars [Frey et al. (2006)]:

\[ VSP = v \times (0.22a + g \times \sin \phi + 0.059) + 1.2 \times 10^{-5} \times v^3 \]

Assumptions:
- \( \Phi \): link’s grade
- \( g \): standard gravity (9.81 m/s^2)
- free flow speed: \( v_f^a = 45 \text{ km/hr} = 12.5 \text{ m/s} \)
- acceleration rate: \( a_{acc} = 3 \text{ m/s}^2 \)
- deceleration rate: \( a_{dec} = 4 \text{ m/s}^2 \)

<table>
<thead>
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<th>Operating mode</th>
<th>NOx [mg/s]</th>
<th>CO [mg/s]</th>
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<tbody>
<tr>
<td>Acceleration</td>
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<td>Deceleration</td>
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<td>Cruising</td>
<td>1.2</td>
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<tr>
<td>Idling</td>
<td>0.3</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Methodology: Transit Emission Rates

Emission rate estimation for diesel buses \[\text{[Zhai et al. (2008)]}:\]

\[
VSP = v \ast (a + g \ast sin\phi + 0.092) + 0.00021 \ast v^3
\]

Assumptions:

- Free flow speed: \( v_f^a = 45 \frac{km}{hr} = 12.5 \frac{m}{s} \)
- Acceleration rate: \( a_{acc} = 2 \frac{m}{s^2} \)
- Deceleration rate: \( a_{dec} = 2 \frac{m}{s^2} \)

<table>
<thead>
<tr>
<th>Operating mode</th>
<th>NOx [mg/s]</th>
<th>CO [mg/s]</th>
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</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>263.5</td>
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<tr>
<td>Deceleration</td>
<td>45.0</td>
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<tr>
<td>Cruising</td>
<td>133.3</td>
<td>37.1</td>
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<tr>
<td>Idling</td>
<td>45.0</td>
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</tr>
</tbody>
</table>
Application: Considered Pollutants

- **Carbon Monoxide (CO):**
  - Detrimental effects on health
  - Interference with oxygen absorption by red blood cells
  - Automobiles contribute 85% of CO emissions in industrialized nations

- **Nitrogen Oxides (NO$_x$):**
  - Irritation of airways, especially lungs
  - Help the formation of other smog components such as ground-level ozone
  - Diesel buses are the primary source of NO$_x$ emissions
Application: Test Site

- $C = 120$ sec
- Intersection flow ratio during peak hour = 0.9
- 6-phase signal
Application: Evaluation Tests

- Two objective functions:
  - Minimize a weighted combination of vehicle delay and emissions
  - Minimize a weighted combination of person delay and emissions

- Intersection flow ratio*: 0.4, 0.6, 0.9

- Deterministic arrivals

- Known and constant auto arrival and passenger occupancy

- Auto passenger occupancy = 1.25 pax/veh

- Varying transit arrivals across the cycle

- Transit passenger occupancy = 30 pax/veh

- One or two transit arrivals in conflicting lane groups

- Pollutants: CO and NOx

*sum of flow ratios (v/s) for all critical lane groups
Results

Minimizing a weighted combination of vehicle delay and CO emissions when there is no transit vehicle at the intersection

- Higher rate of emission reduction for lower values of emission weighting factor
Results

Minimizing a weighted combination of vehicle delay and $NO_x$ emissions when there is a transit vehicle in lane group 8

Intersection flow ratio = 0.4

- Providing priority to the bus to achieve significant emissions saving
- High emissions reduction at the price of low delay increase for very small $\lambda_e$

Intersection flow ratio = 0.9

- Lower flexibility of the system under higher traffic condition
- Steady rate of emissions reduction as delay increases
Results

Relationship between transit delay and $NO_x$ emissions when there is a transit vehicle in lane group 8 when a combination of vehicle delay and $NO_x$ emissions is minimized

- Linear trend between transit delay and $NO_x$ emissions

Intersection flow ratio = 0.4
Results

Minimizing a weighted combination of vehicle delay and CO emissions when there is a transit vehicle in lane group 8

Intersection flow ratio = 0.4

- Lower trade-off between vehicle delay and CO emissions compared to the trade-off between vehicle delay and NOx emissions
- High rate of emission change for low $\lambda_e$
Results

Relationship between transit delay and CO emissions when there is a transit vehicle in lane group 8 and a combination of vehicle delay and CO emissions is minimized.

- Inverse relationship between transit delay and CO emissions

Intersection flow ratio = 0.4
Results

Minimizing a weighted combination of person delay and emissions when there is a transit vehicle in lane group 8 and the intersection flow ratio is 0.4

**Minimizing person delay and $NO_x$ emissions**
- Lower change in $NO_x$ emissions when in the objective function vehicle delay is replaced with person delay

**Minimizing person delay and $CO$ emissions**
- Person delay objective is more conflicting with $CO$ emissions than $NO_x$ emissions
- High rate of emission change for a wide range of weights
Summary of Findings

- Two sets of objectives are highly conflicting:
  - Vehicle delay and $NO_x$ emissions
  - Person delay and $CO$ emissions

- The trade-off between delay and emissions depends on emission rates and vehicles’ passenger occupancy.

- The impact of optimized signal timings on the operation of transit vehicles depends on emission rates used and vehicles’ passenger occupancy.
Summary of Findings

- When there are more than one transit vehicles that are candidate to receive priority, the system has lower flexibility to adjust signal timings.

- The system has higher flexibility to adjust signal timings at low intersection flow ratios.

- Pareto Frontiers can help decision makers determine the best objective function based on their priorities.
**Conclusions**

- **Bi-objective signal control system:**
  - Flexible (person and vehicle delay; various types of pollutants)
  - Generic
  - Can accommodate conflicting transit routes
  - Computationally efficient
Future Work

- Account for oversaturated traffic conditions
- Optimized all signal settings including green times, phase sequence, and cycle length
- Extend the model to signalized arterials
References


QUESTIONS?

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