JOINT TRAFFIC ROUTING AND SIGNAL CONTROL IN A CONNECTED VEHICLE ENVIRONMENT

MICHAEL ZHANG
CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF CALIFORNIA AT DAVIS

FOR
TRANSPORTATION SYSTEM OPTIMIZATION WORKSHOP
MAY 8, 2015 AT
DANIEL J EPSTEIN DEPARTMENT OF INDUSTRIAL ENGINEERING
UNIVERSITY OF SOUTHERN CALIFORNIA
OUTLINE

- The traffic signal control problem
- Three levels of joint routing-signal control
- Dynamic traffic routing & signal control under DUE
- Adaptive routing & signal control without UE
- Future research
THE TRAFFIC LIGHT CONTROL PROBLEM: BASIC SETTING
TRAFFIC CONTROL PROBLEM: CYCLE, PHASES, OFFSETS

Time-space diagram

Progression speed: $S$

$3L$

$2L$

$L$

$\phi_1$

$\phi_2$

$C$

$G_1$

$Y$

$R_1$
TRAFFIC SIGNAL OPERATION

- **Fixed timing plan**
  - Cycle length, green times, and offsets are fixed for a given time period (such as morning peak or evening peak)
  - They can vary across time periods
  - Do not respond to changes in travel demand

- **Vehicle Actuated Plan**
  - Sensors detect traffic demand in real time
  - Green times are extended or terminated based on gaps and max green times
  - Respond to demand changes but resort to fixed timing plan under heavy demand
TRAFFIC SIGNAL TIMING OPTIMIZATION

- Objectives
  - Delay/queue/Number of stops
  - Throughput
  - Progression bandwidth
  - Combinations of the above

- Constraints
  - Bounds on green times
  - Flow conservation
  - Integer cycle constraints on offsets

- Linear problem (e.g. min total queue length)
- Mixed integer linear problem (e.g. max green band)
- Nonlinear problem (e.g., min delay with Webster’s delay formula)
- Mixed integer nonlinear problem (minimize delay and maximize green band)

Traffic demand and travel routes are known and fixed
THREE LEVELS OF FEEDBACK: TRAFFIC CONTROL WITH FLOW REDISTRIBUTION

- Long term: static user equilibrium (UE)
  - Minimize network delay while maintaining static UE traffic assignment (MPEC)
  - e.g., Smith, 1979; 1981; Yang and Yagar, 1995; Ghatee and Hashemi, 2007

- Intermediate term: dynamic user equilibrium (DUE)
  Minimize network delay while maintaining DUE (Dynamic MPEC)

- Short-term: adaptive routing and control without equilibrium
  Local minimization of cycle and phases with real-time hyperpath rerouting
UE route choice behavior: routes with minimum perceived travel time are selected

Signal control plans affects travel times
- Flow capacity drops due to signal timing
- Queue spillbacks due to high demand and low capacity

Minimizing total travel costs

A mathematical program with equilibrium constraints (MPEC)
- Use PATH solver in GAMS
- Global optimum may not be found (due to nonlinearity)
MODELLING FRAMEWORK

\[ \min_{\{g^c(c)\}} TTT \]

**Flow dynamics**

Double-queue link model

\[ q^d_{i,j}(t) \]

\[ q^e_{i,j}(t) \]

Inflow \( p_{i,j}(t) \)

link \((i,j)\)

Exit flow \( v_{i,j}(t) \)

**UE behavior**

Dynamic User Equilibrium Constraints

\[ 0 \leq p^s'_{i,j}(t) \perp (\tau_{i,j}(t) + \pi^s_j(t + \tau_{i,j}(t)) - \pi^s_i(t)) \geq 0 \]

approximation

\[ 0 \leq p^s'_{i,j}(t) \perp (\tau_{i,j}(t) + \pi^s_j(t + \tau^0_{i,j}) - \pi^s_i) \geq 0 \]

**Green time allocation**

Traffic Signal Control Constraints

link 1

\[ g^1_j \]

link 2

\[ g^2_j \]

\[ \overline{C}_{link1} = C_{link1} \frac{g^1_j}{g^1_j + g^2_j} \]

\[ \overline{C}_{link2} = C_{link2} \frac{g^2_j}{g^1_j + g^2_j} \]

**Other constraints**

- Initial condition: empty network
- Terminal condition: traffic cleared
- Non-negativity conditions
- Traffic demand
NUMERICAL RESULTS

Origin-Destination (OD) Demand

1 -> 7 100
3 -> 7 50
13 -> 7 100
15 -> 7 50
2 -> 20 100
3 -> 20 50
5 -> 20 100
15 -> 20 50

## NUMERICAL RESULTS

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>UE constr.</th>
<th>No UE constr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed signal</td>
<td>I</td>
<td>II</td>
</tr>
<tr>
<td>Adaptive signal</td>
<td>III</td>
<td>IV</td>
</tr>
</tbody>
</table>

- 24509 min (local minimum)
- 24957 min
- 18917 min
- 18795 min

![Diagram showing system total travel time](Diagram.png)
ADAPTIVE ROUTING/CONTROL FOR CONNECTED VEHICLES

- Connected Vehicle: Vehicles equipped with wireless communications can “talk” to other vehicles (V2V) or infrastructure (V2I).
- Vehicles equipped with high precision GPS
- Accurate location, speed, and route information can be collected and communicated to travelers and controllers
ADAPTIVE TRAFFIC SIGNAL CONTROL

- Low-density control (for light to medium traffic)
  - A typical vehicle actuated control

- High-density control (for heavy traffic)
  \[
  G_{ij}^{h;g}(t) = \frac{q_{ij}^{h;g}(t)}{\sum_{h,j \in \Gamma(i), h \neq j} q_{ij}^{h;g}(t)} G_{i}^{g}(t)
  \]

- Phase selection control (for very heavy traffic)
  \[
  \left( \varepsilon_{ij}^{l}, G_{ij}^{h;g}(t) \right) = \arg \max_{\varepsilon_{ij}^{l} \varepsilon_{ij}^{l} t_{g} \in [G_{\text{min}}, G_{\text{max}}]} \frac{\text{The estimated number of vehicles passing in phase } \varepsilon_{ij}^{l} \text{ during time } t_{g}}{t_{g}}
  \]
Time-dependent stochastic routing

\[ \lambda^h_{i:s:g}(t) = \min_{j \in \mathcal{E}(i)} \left\{ \sum_{k=1}^{K_{ij}(t)} \left[ \lambda^h_{i:s:g}(t) \left( t + \phi^l_{ij}(t) \right) + \lambda^h_{i:s:g}(t) \left( t + \phi^l_{ij}(t) \right) \right] + \rho^k_{ij}(t) \right\} \]
A 10x3 grid network is used

Three different traffic demand levels considered
- Low density
- Mildly congested
- Highly congested
EFFECTS OF MARKET PENETRATION OF DTR TRAVELERS

Average travel time over the entire simulation horizon with 500 vehicles

Average travel time over the entire simulation horizon with 6000 vehicles
AVERAGE QUEUES LENGTH

Queue in the network with 800 vehicles (Average over 2 mins)

- Fixed Timing Control W/ DTR
- High-Density Algorithm W/ DTR
- Low-Density W/ DTR

Queue in the network with 2800 vehicles (Average over 2 mins)

- Fixed Timing Control W/ DTR
- High-Density Algorithm W/ DTR
- Low-Density W/ DTR
AVERAGE SPEED

Average vehicle speed (km/h) with 1000 vehicles (average over 2 mins) W/ DTR

- Blue line: Fixed Timing Control W/ DTR
- Green line: High-Density Algorithm W/ DTR
- Red line: Low-Density Algorithm W/ DTR

Average vehicle speed (km/h) with 2800 vehicles (average over 2 mins) W/ DTR

- Blue line: Fixed Timing Control W/ DTR
- Green line: High-Density Algorithm W/ DTR
- Red line: Low-Density Algorithm W/ DTR
AVERAGE SPEED: MORE DETAILED VIEW

- “dominate” cycle oscillations

<table>
<thead>
<tr>
<th>Type of Intersection</th>
<th>Cycle Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle(Dominate)</td>
<td>94s</td>
</tr>
<tr>
<td>Corner</td>
<td>34s</td>
</tr>
<tr>
<td>Others</td>
<td>68s</td>
</tr>
</tbody>
</table>
500 vehicles
Slope can be interpreted as the average speed
Phase selection performs best of all
In low density cases, re-routing and non-rerouting don’t have too much difference.
MACROSCOPIC PERFORMANCE-MFD

- 3000 vehicles
- Phase selection performs best of all
- In mildly congested cases, rerouting is more stable than non-rerouting when network is fully loaded.
- And the average speed recovers faster to ‘free flow’ than non-rerouting.
MACROSCOPIC PERFORMANCE-MFD

- 6000 vehicles
- Phase selection performs best of all.
- When network is fully loaded, the slope of rerouting is positive while that of non-rerouting is close to 0 (flat curve) which means the average speed is higher than non-rerouting. (But difference is not very significant)
AVERAGE SPEED EVOLVING

- # of vehicles: 800. Time duration: 1000s
- Left: Fix-timing Control, Right: Low-Density Alg.
- Unit: m/s
# of vehicles: 2800. Time duration: 1000s
Left: Fix-timing, Right: High-volume Alg.
Unit: m/s
CONCLUDING REMARKS

- Traffic signal control cannot ignore traveler’s response (in the form of route choices and induced demand)
- Joint routing/control in different levels can improve overall network performance
- The advent of smart phones and connected vehicles offers the opportunity to operationalize joint routing and signal control
- Joint routing and control presents many challenging optimization problems
  - Adaptive routing/control with coordination
  - Large scale MPEC
  - Stability of adaptive routing/control
ACKNOWLEDGEMENTS

- Collaborators:
  - Students and Postoc
    - Rui Ma
    - Huajun Chai
    - Mani Amoozadeh
    - Dylan Smith
  - Faculty
    - Chen-Nee Chua
    - Dipak Ghosal

- Financial support:
  - The National Science Foundation
REFERENCES


