ADAPTIVE ROUTING AND TRAFFIC CONTROL UNDER THE CONNECTED VEHICLE ENVIRONMENT

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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: $S$

$3L$

$2L$

$L$
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 (e.g., minimize delay over cycle, splits and offsets)

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 rerouting
UE route choice behavior: routes with minimum perceived travel time are selected

Signal control plans affect 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

\[
\begin{align*}
\min_{\{g^{w}(c)\}} & \quad TTT \\
\end{align*}
\]

**Flow dynamics**

Double-queue link model

**Green time allocation**

Traffic Signal Control Constraints

- `link 1`
- `link 2`

\[
\begin{align*}
\bar{C}_{l1} &= C_{l1} \frac{g^j_1}{g^j_1 + g^j_2} \\
\bar{C}_{l2} &= C_{l2} \frac{g^j_2}{g^j_1 + g^j_2}
\end{align*}
\]

**UE behavior**

Dynamic User Equilibrium Constraints

\[
0 \leq p_{(i,j)}^s(t) \perp (\tau_{(i,j)}(t) + \pi_j^s(t + \tau_{(i,j)}(t)) - \pi_i^s(t)) \geq 0
\]

\[
\text{approximation}
\]

\[
0 \leq p_{(i,j)}^s(t) \perp (\tau_{(i,j)}(t) + \pi_j^s(t + \tau_{(i,j)}^0) - \pi_i^s) \geq 0
\]

**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

- **Fixed Signal Control**
  - Scenario I: UE Constraints, 32477 min
  - Scenario II: No UE Constraints, 18917 min

- **Adaptive Signal Control**
  - Scenario III: UE Constraints, 29326 min
  - Scenario IV: No UE Constraints, 18795 min

<table>
<thead>
<tr>
<th>Scenario</th>
<th>UE Constraints</th>
<th>No UE Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Signal</td>
<td>I</td>
<td>II</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adaptive Signal</td>
<td>III</td>
<td>IV</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
DISCUSSIONS ON THE NUMERICAL RESULTS

- MPEC can only solve a local minimum for Scenario III (UE + Adaptive control)
  - Initial values for MPEC is essential
  - Starting from Scenario I solution can lead to a better solution

<table>
<thead>
<tr>
<th>Scenario</th>
<th>I</th>
<th>II</th>
<th>III with default initial value</th>
<th>III with Scenario I initial value</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>High demand level</td>
<td>32477</td>
<td>18917</td>
<td>38243</td>
<td>29326</td>
<td>18795</td>
</tr>
<tr>
<td>Medium demand level</td>
<td>18580</td>
<td>12749</td>
<td>18918</td>
<td>16452</td>
<td>12600</td>
</tr>
<tr>
<td>Low demand level</td>
<td>8785</td>
<td>7648</td>
<td>8935</td>
<td>8775</td>
<td>7541</td>
</tr>
</tbody>
</table>
- 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)
  - \[ \left( \varepsilon_{ij}^{l}, G_{ij}^{h:g}(t) \right) = \arg \max_{(\varepsilon_{ij}^{l} \in \varepsilon_{ij}, t_g \in [G_{min}, G_{max}])} \left\{ \frac{\text{The estimated number of vehicles passing in phase } \varepsilon_{ij}^{l} \text{ during time } t_g}{t_g} \right\} \]
DYNAMIC TRAFFIC ROUTING

- Time-dependent stochastic routing
  - \( \lambda_{i}^{h:s:g}(t) = \min_{j \in \Gamma(i)} \left\{ \sum_{k=1}^{K_{ij}^{g}(t)} \left[ \tau_{ij}^{k;g} \left( t + \phi_{ij}^{l;g}(t) \right) + \lambda_{j}^{i:s:g} \left( t + \phi_{ij}^{l;g}(t) \right) + \tau_{ij}^{k;g} \left( t + \phi_{ij}^{l;g}(t) \right) \right] \cdot \rho_{ij}^{k;g} \left( t + \phi_{ij}^{l;g}(t) \right) \right\} \)
  - \( \lambda_{i}^{h:s:g}(t) \): The minimum cost from node i to destination s at time t in day g, the previous node is h.
  - \( \phi_{ij}^{l;g}(t) \): The delay from intersection i at time t in day g; \( \varepsilon_{ij}^{l} \) is the \( l^{th} \) phase of intersection i whose down stream node is j.
  - \( \tau_{ij}^{k;g}(t) \): the \( k^{th} \) possible link travel time for link (i, j) at time t in day g.
  - \( \rho_{ij}^{k;g}(t) \): the probability for link travel time \( \tau_{ij}^{k;g}(t) \) in day g.
  - \( K_{ij}^{g}(t) \): The total number of possible link travel times for link (i, j) at time t in day g
  - \( \Gamma(i) \): The set of all the adjacent codes of node i.
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 QUEUE LENGTH

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

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

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

Average vehicle speed (km/h) with 2800 vehicles (average over 2 mins) W/ DTR
“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 - 3000 VEHICLES

- 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-6000 VEHICLES

- 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
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  - Faculty
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REFERENCES


REFERENCES


QUEUE VS TIME (LARGE NETWORK)

- Average queue length over time.

Average queue length over time (500 vehicles, 50% are re-routing vehicles) Moving average: step 20

Average queue length over time (3000 vehicles, 50% are re-routing vehicles) Moving average: step 100

Average queue length over time (6000 vehicles, 50% are re-routing vehicles) Moving average: step 100
AVE SPEED VS TIME (LARGE NETWORK)

- Ave speed over time.