CONCURRENT OPTIMIZATION OF SIGNAL PROGRESSION AND CROSSOVER SPACING FOR DIVERGING DIAMOND INTERCHANGES

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Evolution of DDI

- Proposed around early 2000’s
- First DDI opened in 2009
- Able to reduce conflict points for turning movements from and onto the freeway ramps by reversing the through movements at the crossovers
- Currently more than 80 locations around the country

Source: http://www.divergingdiamond.com/index.html

I-44 & Kansas Expressway in Springfield, MO
Research Issues

- Two-phase signal
  - Eastbound through, southbound right, and northbound left
  - Westbound through, southbound left, and northbound right
- Cycle length and green splits can be determined with methods.

Optimal cycle length and signal timing plan for sub-intersections

Optimal distance between stops lines for each movement

Optimal signal offset
Research Issues

Optimal distance between stop lines for each movement

Accommodate queues

Progression

Optimal signal offset

Travel time
Research Issues

- Optimal cycle length and signal timing plan for sub-intersections
- Optimal distance between stops lines for each movement
- Optimal signal offset

- The distances between the stop lines for through and left turn movements are different.
- A set of adjustment variables should be set to determine the proper location of those stop lines based on the crossover spacing.
Model Development

Offset optimization
- Input: cycle length, green splits, cruising speed, crossover spacing

Crossover spacing optimization
- Input: cycle length, green splits, traffic volume, saturation flow rate, offsets

Concurrent optimization of the offset and crossover spacing
- Input: cycle length, green splits, cruising speed, traffic volume, saturation flow rate
Model Development

\[ \text{Max : } \sum_j b_j \]

- \( b_j \): the progression bandwidth for critical movement \( j \)

\[ w_{i,j} + b_j \leq g_{i,j} \]

- \( w_{i,j} \): the part of green time before the specified band used by flows on movement \( j \) at intersection \( i \);
- \( g_{i,j} \): the duration of the phase for movement \( j \) at intersection \( i \).

To make sure that each band only uses its corresponding green phase.

Offset optimization
Model Development

\[ \theta_i + w_{1,1} + \frac{l + l'_i}{v_1 C} + n_{1,1} = \theta_2 + w_{2,1} + n_{2,1} \]

- \( \theta_i \): the offset at intersection \( i \)
- \( C \): cycle length
- \( l \): crossover spacing
- \( l'_i \): the distance adjustment term defined by the position of the stop line
- \( v_j \): the progression speed defined for critical movement \( j \)
- \( n_{i,j} \): integer variables.

\[ \theta_2 + g_2 + w_{2,2} + \frac{l + l'_2}{v_2 C} + n_{2,2} = \theta_1 + g_1 + w_{1,2} + n_{1,2} \]

\[ \theta_1 + g_1 + w_{1,3} + \frac{l + l'_3}{v_3 C} + n_{1,3} = \theta_2 + w_{2,3} + n_{2,3} \]

\[ \theta_2 + w_{2,4} + \frac{l + l'_4}{v_4 C} + n_{2,4} = \theta_1 + g_1 + w_{1,4} + n_{1,4} \]

To determine the proper offsets based on travel time
Queue length calculation:

\[ \tau = \frac{(Cr + \delta)\alpha q}{s - \alpha q} \]

\( \tau \): the distance between the stop bar and the end of queue before it is fully discharged; 
\( r \): the fraction of red phase; 
\( \delta \): the lost time in seconds; 
\( q \): the volume; 
\( \alpha \): the corresponding lane use factor; 
\( s \): the saturation flow rate.
Model Development

Through vehicles not experiencing signal progression

Off-ramp vehicles not experiencing signal progression

\[
\frac{s}{s - \alpha q_j} \left[ \alpha q_2 \left( 1 - g_2 - b_2 \right) \frac{C}{g_2} + \alpha q_4 \left( g_2 - b_4 \right) \frac{C}{g_2} \right] \leq \left( l + l'_4 \right) / h, \quad j = 2, 4
\]

\[
\frac{s}{s - \alpha q_j} \left[ \alpha q_1 \left( g_1 - b_1 \right) \frac{C}{g_1} + \alpha q_3 \left( 1 - g_1 - b_3 \right) \frac{C}{1 - g_1} \right] \leq \left( l + l'_3 \right) / h, \quad j = 1, 3
\]

- To avoid queue spillback regardless of the signal phase at the upstream intersection
- Based on the given bandwidths, which can be directly computed from the offset.

\( h \): the spatial headway of vehicles between two sub-intersections
Model Development

**Concurrent optimization of offset and crossover spacing**

Max: \( \sum b_j - \frac{l/vC}{M} \)

- Both offset and crossover spacing are decision variables.
- The proposed model is able to avoid queue spillback and generate maximum progression bands.

\( w_{i,j} + b_j < g_j, \quad w_j \geq 0 \)

To make sure that each band only uses its green phase

\( \theta_1 + w_{i,1} + \frac{l + l'_1}{v_1 C} + n_{i,1} = \theta_2 + w_{2,1} + n_{2,1} \)
\( \theta_2 + g_2 + w_{2,2} + \frac{l + l'_2}{v_2 C} + n_{2,2} = \theta_1 + g_1 + w_{1,2} + n_{1,2} \)

To determine the proper offsets based on travel time

\( \theta_1 + g_1 + w_{i,3} + \frac{l + l'_3}{v_3 C} + n_{i,3} = \theta_2 + w_{2,3} + n_{2,3} \)
\( \theta_2 + w_{2,4} + \frac{l + l'_4}{v_4 C} + n_{2,4} = \theta_1 + g_1 + w_{1,4} + n_{1,4} \)

To estimate the queue lengths and force the crossover spacing to be larger

\( \frac{s}{s - \alpha q_j}(\alpha q_2 (1 - g_2 - b_2) C / g_2 + \alpha q_4 (g_2 - b_4) C / g_3) \leq (l + l'_4) / h, \quad j = 2, 4 \)

\( \frac{s}{s - \alpha q_j}[(\alpha q_1 (g_1 - b_1) C / g_1 + \alpha q_3 (1 - g_1 - b_3) C / (1 - g_1))] \leq (l + l'_3) / h, \quad j = 1, 3 \)
Case Study

- A DDI at I-70 & Mid Rivers Mall Dr. in Saint Peters, MO
- Adopted PM peak demand data from a traffic survey in April 2016
- Cycle length and green splits are calculated based on volume.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Left (vph)</th>
<th>Through (vph)</th>
<th>Right (vph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southbound</td>
<td>120</td>
<td>345</td>
<td>490</td>
</tr>
<tr>
<td>Northbound</td>
<td>150</td>
<td>945</td>
<td>595</td>
</tr>
<tr>
<td>Eastbound</td>
<td>85</td>
<td>--</td>
<td>635</td>
</tr>
<tr>
<td>Westbound</td>
<td>1185</td>
<td>--</td>
<td>150</td>
</tr>
</tbody>
</table>
Case Study

- Optimization results and simulation design
  - 4 different lengths for the crossover spacing
  - 2 volume levels

<table>
<thead>
<tr>
<th>Cases</th>
<th>Current volume</th>
<th>Projected volume (1.4 times)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crossover spacing (ft)</td>
<td>Offset (sec)</td>
</tr>
<tr>
<td>1. Actual</td>
<td>469</td>
<td>24</td>
</tr>
<tr>
<td>2. Shorter</td>
<td>547</td>
<td>43</td>
</tr>
<tr>
<td>3. Optimized</td>
<td>624</td>
<td>42</td>
</tr>
<tr>
<td>4. Long</td>
<td>950</td>
<td>49</td>
</tr>
</tbody>
</table>
Case Study

- Simulation results (current volume)
  - *The optimized crossover spacing outperforms other three cases.*
  - *Increasing the crossover spacing towards the optimal one can result in less traffic delay.*
  - *A crossover spacing longer than the optimal one may not yield the benefits.*
Case Study

- Simulation results (projected volume, 1.4 times of the current volume)
  - The proposed model can still outperform other cases.
  - The optimal design yields more benefits under the higher volume scenario.
Case Study

- Time-dependent queue length at the South intersection (current volume)
  - The concurrently optimized crossover spacing and offset are able to alleviate queue spillback due to volume fluctuation.
Conclusions and Future Study

- An optimization model to fully account for the interdependent relation between the crossover spacing and the signal offset in a DDI

- Simulations to evaluate the performance of the proposed model
  - the DDI with the concurrently optimized crossover spacing and offset can yield the shortest delays and fewest number of stops
  - the DDI with the optimized design features can effectively cope with potential queue spillback at the crossovers

- Future study
  - a method to determine whether or not to set signals for all off-ramp flows at those DDI sub-intersections
  - a method to estimate the impacts to the adjacent intersections and close exits on the freeway
Acknowledgement

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