0-6920: PROACTIVE TRAFFIC SIGNAL TIMING AND COORDINATION FOR CONGESTION MITIGATION ON ARTERIAL ROADS

TxDOT Houston District
Address Congestion
Contents

- Background
- Research Objective
- Proactive Signal Control Concept
- Simulation
- Field Experiment
- Summary
- Large-Scale Implementation
Traffic Congestion

- National congestion
  - 5 million-hour delay of daily commutes;
  - $100 billion financial lost:
- State-wide congestion - Texas
  - 60 –hour delay annually for each commuter in Houston Area;
  - Increase to 100 hours in 2025;
  - $12 billion financial lost in 2025:

Background

Typical Signal Control Algorithms

- **Fixed-time Plan**
  - The phase sequence and the duration of each phase are predefined.

- **Reactive/Actuated Control**
  - The phase at each time interval is assigned to the one with the highest delay -- *found by detectors*.

- **Proactive Control**
  - The phase at each time interval is assigned to the one with this highest *predicted* delay based on the *short-term predicted* timing – varying traffic volume.
Research Objectives

- **Proactive Signal Control System**
  - Develop a fully collaborative vehicle-signal control systems
    - Utilize communications among loop detectors, traffic signals and connected vehicles (if any);
    - Gather real-time traffic conditions and predict short-term conditions;
    - Update signal phasing and timing (SPaT) plan based on the short-time traffic prediction.
  - Optimize the performance of signalized intersections
    - Mitigate traffic congestions, vehicle emissions, and fuel consumption;
    - Reduce travel time and stop delay in the vicinities of intersections
Proactive Signal Control Concept

- Collaborative Vehicle-signal Control Environment
  - Connections among vehicles, loop detectors and signals
  - Optimize phase assignments and duration without being restricted by cycle length
  - Optimize Signal Phasing and Timing (SPaT) plans of multiple signals with coordination
Signal Control at Intersections

- Vehicle approaches (lane group)
- Phases
- Detectors
- Delay on each approach

\[ D_i(t) = \sum_{\tau=0}^{t} \left( N_{I,i}(\tau) - N_{O,i}(\tau) - \frac{l_i}{v_i} \right) \]

- \( N_{I,i}(t) \): Cumulative inflow at the IN detector;
- \( N_{O,i}(t) \): Cumulative outflow at the OUT detector;
- \( l_i \): Distance between the IN and OUT detectors;
- \( v_i \): Road speed limit.
Signal Control at Intersections

**Signal Optimization:**

\[ \min_{p_k(t), \forall k=1,2,\ldots,P} \sum_{i=1}^{N} D_i(T_0) \]

s.t.

\[ N_{I,i}(t) = f_{I,i}(t); \]
\[ N_{O,i}(t) = f_{O,i}(t); \]
\[ f_{O,i}(t) = \begin{cases} 0 & m_i(t) = 0 \\ Q_i & m_i(t) = 1 \end{cases}; \]
\[ m_i(t) = \begin{cases} 1 & i \in M_k, p_k(t) = 1, \forall i = 1,2,\ldots,N \\ 0 & \text{otherwise} \end{cases} \]

- \( f_{I,i}(t) \): Flow rate detected by the IN detector at time \( t \);
- \( f_{O,i}(t) \): Flow rate detected by the OUT detector at time \( t \);
- \( Q_i \): Road capacity for the approach \( i \);
- \( P \): total number of phases;
- \( N \): total number of approaches;
- \( p_k(t) \): signal indicator for the phase \( k \);
  - 0: red; 1: green.
- \( m_i(t) \): Permissive indicator for the approach \( i \);
  - 0: prohibited; 1: permitted.
- \( M_k \): set of approaches associated with the phase \( k \).
Proactive Signal Control Concept

- System Development

Time interval $t$

Current Delay Calculation

Connected Vehicles

Phase 1

Phase P

Predicted Delay

Predicted Delay

Activate the optimal phase at time interval $t+1$

$D_i(t) = \sum_{\tau=0}^{t} \left( N_{I,i}(\tau) - N_{O,i}(\tau) - \frac{l_i}{v_i} \right)$

$d_k(t_{n+1}) = \sum_{i=1}^{N} D_i(t_n) + \sum_{t=t_n}^{t_{n+1}} \left( N_{I,i}^k(t) - N_{O,i}^k(t) - \frac{L_i}{v_i} \right)$

$N_{I,i}^k(t) - N_{I,i}^k(t-1) = f_{I,i}(t), i = 1,2,\ldots,N;$

$N_{O,i}^p(t) - N_{O,i}^p(t-1) = \begin{cases} Q_i & i \in \mathcal{M}_p \\ 0 & \text{otherwise} \end{cases}$

Cumulative Inflow at the IN detector

$f_{I,i}(t)$
Test based on Simulation

- Testbed – FM1960
  - Four Intersections
    - Wortham Blvd.
    - N Eldridge Pkwy.
    - Windermere Lake Blvd.
    - Fallbrook Dr.
Test based on Simulation

- TestBed – Major road (FM1960)
  - Total Length
    - 7713 Feet
  - Speed Limits on the major road
    - 40 mph
  - Number of lanes of the major road
    - Three lanes, and additional one left-turn lane ahead of each intersection
## Test based on Simulation

### Testbed – Minor roads

<table>
<thead>
<tr>
<th>Direction</th>
<th>Intersection</th>
<th>Intersection Name</th>
<th>Speed Limit (mile/hour)</th>
<th>Center to Center Distance (feet)</th>
<th>Cumulative Distance from Start point (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>West to East</td>
<td>Start</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>A</td>
<td>Wortham Blvd.</td>
<td>35 (N), 35(S)</td>
<td>984*</td>
<td>984</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>N Eldridge Pkwy.</td>
<td>40 (N), 40(S)</td>
<td>2247</td>
<td>3232</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Windermere Lake Blvd.</td>
<td>30(S)</td>
<td>2215</td>
<td>5446</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Fallbrook Dr.</td>
<td>30 (N), 35 (S)</td>
<td>1328</td>
<td>6775</td>
<td></td>
</tr>
<tr>
<td></td>
<td>End</td>
<td></td>
<td>820</td>
<td>7713</td>
<td></td>
</tr>
</tbody>
</table>
Methodological Framework

Data Collection

- Geometric Properties
- Existing Signal Plans
- Real Traffic Data (volume and occupancy)

Simulation in INTEGRATION/VISSIM

- Build Testbed Model in Integration/VISSIM
- Simulation Verification: Simulated v.s. Observed Traffic Flow

Implement Proactive Signal Control in Simulation

Field Test
### Data Collection

- The road traffic data was collected from 11 am, 04/01/16 to 7 pm, 04/07/16;
- The data was read from the loop detectors for every 1 minute;
- The data was summarized as every 15 minutes for each phase to measure the congestion level of the test bed.
- **Hourly Volume for Phase 5** (Left-turn traffic movements at major road FM 1960, Intersection B at N Eldridge Pkwy)
- Occupancies for Phase 5 (Left-turn traffic movements at major road FM 1960, Intersection B at N Eldridge Pkwy)
Test based on Simulation

- Simulation Verification
  
  - Based on the existing signal plan and the collected traffic data, two simulation packages, INTEGRATION and VISSIM, were used to simulate the traffic of the testbed.

Eastbound, in-flow at major road in a weekday

Eastbound, out-flow at major road in a weekday
Test based on Simulation

- **Simulation Verification**
  - Based on the existing signal plan and the collected traffic data, two simulation packages, *INTEGRATION* and *VISSIM*, were used to simulate the traffic of the testbed.

**Westbound, in-flow at major road in a weekday**

**Westbound, out-flow at major road in a weekday**
Test based on Simulation

- **Simulation Verification**
  - Based on the existing signal plan and the collected traffic data, two simulation packages, *INTEGRATION* and *VISSIM*, were used to simulate the traffic of the testbed.

![Flow vs Time - Westbound, in-flow at major road in a weekend](image1)

![Flow vs Time - Westbound, out-flow at major road in a weekend](image2)
### System Evaluation

- Performance on the major road, FM 1960 (Assume the existing of connected vehicles)

#### Overall network performance

<table>
<thead>
<tr>
<th>Measurements (per trip)</th>
<th>Weekday</th>
<th></th>
<th></th>
<th></th>
<th>Weekend</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td>Diff</td>
<td>Before</td>
<td>After</td>
<td>Diff</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Travel Distance (km)</td>
<td>1.64</td>
<td>1.64</td>
<td>0%</td>
<td>1.74</td>
<td>1.74</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Travel Time (second)</td>
<td>240.29</td>
<td>144.54</td>
<td>-40%</td>
<td>543.88</td>
<td>119.7</td>
<td>-78%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delay (second)</td>
<td>166.92</td>
<td>41.67</td>
<td>-75%</td>
<td>207.98</td>
<td>42.52</td>
<td>-80%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stop Delay (second)</td>
<td>107.34</td>
<td>14.68</td>
<td>-86%</td>
<td>131.31</td>
<td>14.44</td>
<td>-89%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle Stops</td>
<td>2.65</td>
<td>1.96</td>
<td>-26%</td>
<td>2.88</td>
<td>2</td>
<td>-31%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Usage (liter)</td>
<td>0.34</td>
<td>0.27</td>
<td>-21%</td>
<td>0.37</td>
<td>0.28</td>
<td>-24%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC (gram)</td>
<td>1.78</td>
<td>2.05</td>
<td>15%</td>
<td>1.8</td>
<td>2.07</td>
<td>15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO (gram)</td>
<td>44.93</td>
<td>52.87</td>
<td>18%</td>
<td>45.11</td>
<td>53.47</td>
<td>19%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOx (gram)</td>
<td>0.99</td>
<td>0.92</td>
<td>-7%</td>
<td>1.05</td>
<td>0.95</td>
<td>-10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO2 (gram)</td>
<td>713.91</td>
<td>566.31</td>
<td>-21%</td>
<td>786.46</td>
<td>589.04</td>
<td>-25%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## System Evaluation

- Performance on one minor road, N. Eldridge Pkwy. *(Assume the existing of connected vehicles)*

### Overall network performance in a weekday

<table>
<thead>
<tr>
<th>Approaches</th>
<th>Max Queue Length (veh)</th>
<th>Average Delay (second)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>East Bound, FM1960</td>
<td>34.4</td>
<td>16.5</td>
</tr>
<tr>
<td>West Bound, FM1960</td>
<td>50.8</td>
<td>14.1</td>
</tr>
<tr>
<td>North Bound, Eldridge Pkwy</td>
<td>11.9</td>
<td>2.7</td>
</tr>
<tr>
<td>South Bound, Eldridge Pkwy</td>
<td>5.9</td>
<td>1.1</td>
</tr>
</tbody>
</table>

### Overall network performance in a weekend

<table>
<thead>
<tr>
<th>Approaches</th>
<th>Max Queue Length (veh)</th>
<th>Average Delay (second)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>East Bound, FM1960</td>
<td>34.4</td>
<td>16.5</td>
</tr>
<tr>
<td>West Bound, FM1960</td>
<td>50.8</td>
<td>14.1</td>
</tr>
<tr>
<td>North Bound, Eldridge Pkwy</td>
<td>11.9</td>
<td>2.7</td>
</tr>
<tr>
<td>South Bound, Eldridge Pkwy</td>
<td>5.9</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Field Test

- Test Bed 2: NASA ROAD 1
### Test Bed 2: NASA ROAD 1

#### Phase and detector information

<table>
<thead>
<tr>
<th>Approach Number</th>
<th>Phase Number</th>
<th>Detector Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>4(SBD)</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1(SBD)</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>5, 13, 14, 15 (UD)</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>3(SBD)</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2(UD)</td>
</tr>
</tbody>
</table>

Existing signal control: actuated signal control
Field Test

- Test Bed 2: NASA ROAD 1

Logic Statement that can be applied

```
Phase, P = n
Det Occupancy > [D] %
```

- YES
- Call P = n

- NO

```
Det Volume > [V]
```

- YES
- Call P = n

- NO
- No Call

Two key parameters:
1. Occupancy
2. Volume

VISSIM has a package embedded to simulate this controller
Test Bed 2: NASA ROAD 1

Critical values for volume and occupancy

<table>
<thead>
<tr>
<th>Phase Number</th>
<th>Detector</th>
<th>Volume</th>
<th>Occupancy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 (SBD)</td>
<td>2</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>2 (UD)</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3 (SBD)</td>
<td>2</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>4 (SBD)</td>
<td>2</td>
<td>70</td>
</tr>
<tr>
<td>6</td>
<td>5 (SBD)</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13 (SBD)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14 (SBD)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 (SBD)</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Logic Statement Setting in ASC/3-2100 Controller in VISSIM
Test Bed 2: NASA ROAD 1

Change of parameter values

<table>
<thead>
<tr>
<th>Phase</th>
<th>Minimum green time</th>
<th>Maximum green time</th>
<th>Vehicle Extension time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (actuated)</td>
<td>5</td>
<td>20</td>
<td>2.0</td>
</tr>
<tr>
<td>1* (proactive)</td>
<td>0</td>
<td>20</td>
<td>3.0</td>
</tr>
<tr>
<td>2 (actuated)</td>
<td>25</td>
<td>60</td>
<td>3.0</td>
</tr>
<tr>
<td>2* (proactive)</td>
<td>5</td>
<td>70</td>
<td>5.0</td>
</tr>
<tr>
<td>3 (actuated)</td>
<td>5</td>
<td>15</td>
<td>2.0</td>
</tr>
<tr>
<td>3* (proactive)</td>
<td>0</td>
<td>20</td>
<td>3.0</td>
</tr>
<tr>
<td>4 (actuated)</td>
<td>5</td>
<td>25</td>
<td>2.0</td>
</tr>
<tr>
<td>4* (proactive)</td>
<td>0</td>
<td>30</td>
<td>3.0</td>
</tr>
<tr>
<td>6 (actuated)</td>
<td>25</td>
<td>60</td>
<td>3.0</td>
</tr>
<tr>
<td>6* (proactive)</td>
<td>10</td>
<td>90</td>
<td>5.0</td>
</tr>
</tbody>
</table>

The highlighted values represent the corresponding changes.
• Test Bed 2: NASA ROAD 1

Date of Field Observation
- Proactive Signal Control (November 22, 2016)
- Actuated Signal Control (December 9, 2016)

Weekday Peak Hour
- Morning Peak (Observation from 6:30am to 9:00am)
- Evening Peak (Observation from 3:00pm to 5:30pm)
### Test Bed 2: NASA ROAD 1

Evaluation of the proactive algorithm based VISSIM simulation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Actuated Signal Control</th>
<th>Proactive Signal Control</th>
<th>Diff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Delay (seconds)</td>
<td>6.71</td>
<td>6.00</td>
<td>-11%</td>
</tr>
<tr>
<td>Average Number of Stops</td>
<td>0.29</td>
<td>0.26</td>
<td>-10%</td>
</tr>
<tr>
<td>Average Stop delay (seconds)</td>
<td>3.28</td>
<td>2.54</td>
<td>-29%</td>
</tr>
<tr>
<td>Total Delay (seconds)</td>
<td>4878</td>
<td>4359</td>
<td>-13%</td>
</tr>
<tr>
<td>Speed Average (mile/hour)</td>
<td>60.84</td>
<td>61.59</td>
<td>+1.2%</td>
</tr>
</tbody>
</table>
Results

- Test Bed 2: NASA ROAD 1

Field data observations: Phase 1 (left-turn from the major road to the minor road, east-north)
Test Bed 2: NASA ROAD 1

Field data observations: Phase 1 (left-turn from the major road to the minor road, east-north)
Results

- Test Bed 2: NASA ROAD 1

Field data observations: Phase 6 (eastbound through traffic on the major road)

![Graph showing vehicle per hour over time](image)
### Test Bed 2: NASA ROAD 1

Field data observations: Phase 6 (eastbound through traffic on the major road)
## Test Bed 2: NASA ROAD 1

### Evaluation of the proactive algorithm based field observation

<table>
<thead>
<tr>
<th>Approach</th>
<th>Parameter</th>
<th>Actuated Control</th>
<th>Proactive Control</th>
<th>Diff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Approach</td>
<td>Average Queue Length</td>
<td>24.80</td>
<td>10.00</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Maximum Queue Length</td>
<td>39.00</td>
<td>21.00</td>
<td>46</td>
</tr>
<tr>
<td>Minor Approach</td>
<td>Average Waiting Time</td>
<td>47.21</td>
<td>36.00</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Max Waiting Time</td>
<td>70.00</td>
<td>60.00</td>
<td>14</td>
</tr>
</tbody>
</table>
The proactive control system can significantly mitigate road congestion on the test bed, and also reduce emission and fuel consumption.

- From simulation (assuming connected vehicles existing in the network), it is seen that the vehicle delay reduced as high as 80%; the average number of stops of each vehicle reduced from 2.8 to 2; and the stop delay reduced up to 89%;
- On weekdays, the fuel consumption and CO2 is reduced about 21%, and 25% on weekends: this is equivalent to $2,400/day savings of gas on weekdays, and $3,270 on weekends (based on simulation, assuming connected vehicles existing in the network).

The field experiments also reports positive results:

- The proactive signal control system increases the average traffic volumes during peak hours.
- No complaint were received after the implementation
- The average queue length on the major road can be reduced up to 60%, and the average waiting time of vehicles on the minor road decreases up to 24%.
30 Intersections at the Greater Houston Area

- Three testbeds (FM 528, SH 242 and FM 1464), which have consecutive intersections, and are installed with an Ethernet Programmable Automation Controller (EPAC)
- Other separate 8 intersections are using the diamond controller mechanism.
What’s Next

- Implementation of FM 528 corridor
- Intersection spacing and traffic volume at different time of day
- System perform better during Free mode operation
- Free mode operation Vs. Coordination mode
- Ability to automate the operation mode base on conditions
- Machine learning for the future
Contact

Steve Chiu, EIT
Texas Department of Transportation
Houston District

Steve.Chiu@txdot.gov
P: (713) 802-5936