Real-time Signal Control to Mitigate Queue Spillback at the Freeway Off-ramp

Gang-Len Chang
Xianfeng Yang
Department of Civil & Environmental Engineering
University of Maryland
Problem Nature

Since the operational performance of a freeway segment and its neighboring local streets are often mutually dependent, all related studies could be grouped into two categories:

- On-ramp metering control
- Off-ramp signal control

In review of the literature, most studies focused on the on-ramp metering controls while the equally critical issue, off-ramp control, has not yet received adequate attention.
**Problem Nature**

- **Problem Description**

  - Most drivers do not tend to segregate themselves by destination well in advance of an off-ramp, but rather make most of their lane-changing decisions at the last moment.
  - The exit queue at an off-ramp might *spread laterally upstream*, and *spill back to the freeway mainline*.
  - *Congested conditions at downstream intersections* can lead to a long traffic queue at the off-ramp, and the queue spillback may propagate to upstream and block freeway lanes.
To analyze the interrelations between off-ramp queue and local traffic, a freeway segment in Zhubei, Taiwan was selected as the study site:

- The traffic data were collected from 16:30 to 21:30 on April 25, 2013
- Loop detectors are installed at the upstream and downstream of the off-ramp entry to collect speeds and flow rates of the approaching vehicles.
- A video camera has also been installed near the bottleneck area
Problem Nature

- Field Observations

During the period of 17:00 – 20:30, one can observe significant speed drops on all the three freeway travel lanes:

- Lane 3, nearest to the spillback lane, has dropped its speed to 20 km/h;
- After the traffic flows pass the off-ramp entry, the speeds on all three lanes can quickly recover to 90 km/h;
- The presence of queue spillback has also been recorded with the video camera during the congested period.
Real-time Signal Control

Real-time Signal Adjustment:

- Due to the traffic fluctuations, pre-timed control strategy may encounter its limitations in applications.
- When the potential queue spillback is predicted, under some pre-defined conditions, a real-time control strategy will be activated to offer off-ramp traffic flows with progression priority, and let those queuing vehicles to pass through the downstream intersections quickly.
Real-time Control Framework

The operational process for activating the priority control consists of the following parts:

- **1) On-line Data collection**
  - For the target freeway segment, the data collection is focused on recording the upstream traffic flow/speed and the outflow at the off-ramp.
  - Detectors at local arterials are used to estimate the congestion level at nearby intersections, which is defined by the queue over link length ratio at each critical link.
Real-time Control Framework

- **2) Queue Estimation**
  - To prevent queue spillback at the off-ramp, a queue model is developed to estimate the queue length in the horizon of several signal cycles.
  - Given the potential queue spillback information, a control priority will be selected to discharge the off-ramp queues.
  - The dynamic proactive control can be used to activate the priority strategy prior to the formation of queue spillback.
2) Queue Estimation

- the length of detection zone (distance between two loops) can affect the function of detectors;

- short detection zone can be more efficiently to count the number of vehicles;

- observed 100% occupancy measurements is an indication of having stopped vehicles over the long detection zone;

- A dual-zone detector is used in this study to provide the functions for both short and long detection zones.
2) **Queue Estimation**

To take advantage of information both short and long loop detectors, dual-zone detectors are implemented at both upstream and downstream of the off-ramp, as shown in the following figure:
Real-time Control Framework

2) Queue Estimation

With respect to different congestion levels, four scenarios may be encountered during the queue estimation process.

1) When the inflow exceeds the discharging capacity at the downstream of the off-ramp, the queue may be built up quickly and spillbacks to the freeway mainline.

2) During the green time, the traffic queue could be fully discharged.

3) The traffic queue is not cleared after the green phase and some residual queuing vehicles remain on the off-ramp.

4) Queue spillover at the downstream link may affect the queue discharging process and the effective green time would be less than the given green time.
2) **Queue Estimation**

To address the queue estimation under different scenarios, the following figure shows the flowchart of the model:

- **Data Obtained**
  - Check the upstream detector data
  - Spillback to the upstream?
    - Yes: Give queue spillback warning
    - No: Queue Estimation
  - Queue cleared during green time?
    - Yes: Model 1
    - No: Model 2
2) **Queue Estimation**

Model 1:

Assuming a fixed travel speed on the off-ramp, then the travel time between upstream and downstream detectors is given by:

\[ t = \frac{L}{v} \]

Where \( L \) denotes the distance between two detectors and \( v \) is the average travel speed.

Since queue is fully discharged, at time \( k \), the number of moving vehicles between two detectors is equaled to the number of vehicles passed the upstream detector during time period \([k-t, k]\):

\[ N_k = q_u(k - t, k) \]

Where \( q_u(m,n) \) is the detected number of vehicles by the upstream detector during time \([m, n]\).
2) **Queue Estimation**

Model 1:

Queue is fully discharged

Then, at time “g”, the total number of vehicles between two detectors is given by

\[
N_g = N_k + q_u(k, g) - q_d(k, g)
\]

Where \( q_d(m, n) \) is the detected number of vehicles by the downstream detector during time period \([m, n]\).

During the red phase, no queuing vehicle is discharged. Hence, at the end of cycle, the total number of vehicles between two detectors is:

\[
N_{g+r} = N_g + q_u(g, g+r) - q_d(g, g+r)
\]
2) **Queue Estimation**

Model 1:

Queue is fully discharged

Therefore, the queue length at the end of cycle could be approximately computed as:

\[ Q_{g+r} = N_{g+r} + N_c \]

Where \( N_c \) is a constant, which indicates the number of vehicles between downstream detector and stop line.
2) **Queue Estimation** (*queue cleared at the end of green*)

Model 2:

At the end of red time, the total number of vehicles between two detectors is given by:

\[
N_{g+r} = q_u (k - t, g + r)
\]

Similarly, the queue length at the end of cycle could be computed by:

\[
Q_{g+r} = N_{g+r} + N_c
\]
3) Congestion Level Evaluation

- Considering the relationship between flow, density, and speed, the proposed control system uses the speed and flow rate obtained from the freeway upstream detector as the measurement of freeway congestion.

- Since the signal priority given to the off-ramp traffic flows will cause negative impacts to other local traffic movements, the congestion level at those impacted links are defined by the ratios of queue/ link length.
4) **Priority Decision**

- **Condition 1: Freeway congestion level < Threshold**

  When the detected speed near the off-ramp is higher than the critical speed, and the detected flow rate is below the threshold, the impact caused by queue spillback from the off-ramp will be very limited. Hence, *no priority control is required* for this type of condition.

- **Condition 2: Freeway congestion level > Threshold; and Arterial congestion level < Threshold**

  If the estimated freeway congestion level exceeds the threshold while the arterial congestion level is below the threshold, one shall select the *unconditional priority control strategy to discharge all queuing vehicles at the off-ramp*.
4) **Priority Decision**

- Condition 3: Freeway congestion level > Threshold; and Arterial congestion level > Threshold

If the congestion levels at both freeway and local arterial exceed their respective thresholds, a **conditional priority strategy**, which can limit the negative impacts to the arterial, shall be activated.
Real-time Control Framework

Start

i=1

Criterion satisfied?

Yes

Unconditional Priority Control in next cycle

No

Conditional Priority Control in next cycle

Data Collection

Cycle i Normal Signal Control

Freeway Data Collection

Volume Prediction Model

Off-ramp Queue Prediction

Freeway Congestion Level Evaluation

Arterial Data Collection

Arterial Congestion Level Evaluation

Potential Spillback?

Yes

Priority Decision

No

i=i+1

i=i+1

i=i+1

i=i+1

Start

i=1
Dynamic Priority Control Strategy

To effectively discharge queuing vehicles at the off-ramp, one essential step is to identify the proper control strategy.

**Unconditional Priority Control:** the signal timings at the impacted intersections will be adjusted to discharge all the queuing vehicles at the off-ramp
Dynamic Priority Control Strategy

Conditional Priority Control:
Instead of discharging all the queuing vehicles at the off-ramp to pass the downstream intersections, conditional priority strategy allows some residual queues at these intersections to minimize the impacts to other local traffic movements.
Unconditional Priority Control

Note that the **priority decision** will be made when the potential queue spillback at the off-ramp is detected. The entire decision-making process for the unconditional priority control includes the follows steps:

**Step 1:** Collect the **pre-timed signal plans** at each local intersection within the impacted boundaries; **estimate the current queue length** at the off-ramp.

**Step 2:** Compute the **green bandwidth for progression** of the off-ramp traffic movement.

Given the current queue length $q_1$ at the off-ramp, the green bandwidth can be computed as follows:

$$b = \frac{q_1}{s}$$
Step 3: **Set the signal progression**

Let the intersection connected to the off-ramp exit be denoted as intersection “1”, and then number the other impacted intersections along the progression path.

The key parameters are listed in the following figure:
Step 3.1: Compute the extended green time $e_l$ and $e_r$, based on the ratio of the red phase duration.

$$e_r = \max\left(\frac{R_r (b - g_l)}{R_l + R_r}, 0\right)$$

$$e_l = \max\left(\frac{R_l (b - g_l)}{R_l + R_r}, 0\right)$$

where, $R_l$ ($R_r$) is the total red time at the left (right) side of the green band; $g_l$ is the original green time of the phase provides right-of-way to off-ramp flows.
Unconditional Priority Control

**Step 3.2: Compute the green time $\bar{g}_i$ for the off-ramp path at intersection $i$;**

To ensure traffic progression, the initial queue discharging time at the downstream links should be considered. Hence, the green time, $\bar{g}_i$, shall be given by:

$$\bar{g}_i = \max(b + \sum_{j=2}^{i} q_j / s, g_i)$$

Where, $q_j$ is the initial queue at the target link of intersection $j$.

**Step 3.3: Compute the length of $w_i$;**

$$w_2 = R_1 - e_i + t_{1,2} - \theta_2$$

$$w_i = \theta_{i-1} - \theta_i + w_{i-1} + t_{i-1,i} - q_i / s; \quad i > 2$$

where, $t_{i-1,i}$ is the travel time between intersection $i-1$ and $i$. Also note that $\theta_i$ could be a negative value.
Step 4: Re-assign the remaining green time to other phases

By extending the green band of the priority path, the green times of other phases need to be reduced to keep the cycle length unchanged.

To balance the impact to those phases, the system will reduce the green times with the same ratio of their original green times.

Hence, at each intersection, the remaining green time for each reduced phase is computed by:

\[
g_j = g_j - \frac{g_j}{\sum_{k\in \delta, k \neq i} g_k} (g_i - g_i)
\]

where, \(\delta\) is the set of all phases; \(i\) is the index of extended (target) phase; \(g_j\) is the original green time of phase \(j\); \(\overline{g_j}\) is the re-assigned green time for phase \(j\).
Step 4: Re-assign the remaining green time to other phases

For example:

For one signal cycle consists of four phases (A: 20 secs; B: 15 secs; C: 15 secs; D 25 secs). To provide the priority control, the system assigned 10 secs of green extension to phase D. Then the remaining green times of the other three phases are given by:

\[
\bar{g}_A = g_A - \frac{g_A}{\sum_{k \in \delta, k \neq i} g_k} (g_D - g_D) = 20 - \frac{20}{20 + 15 + 15} \times 10 = 20 - 4 = 16 \text{ secs}
\]

\[
\bar{g}_B = g_B - \frac{g_B}{\sum_{k \in \delta, k \neq i} g_k} (g_D - g_D) = 15 - \frac{15}{20 + 15 + 15} \times 10 = 15 - 3 = 12 \text{ secs}
\]

\[
\bar{g}_C = g_C - \frac{g_C}{\sum_{k \in \delta, k \neq i} g_k} (g_D - g_D) = 15 - \frac{15}{20 + 15 + 15} \times 10 = 15 - 3 = 12 \text{ secs}
\]
Step 5: Design the signal transition

Given the computation results from previous steps, the following figure shows an example of signal transition between a pre-timed and a real-time signal cycle.

After implementing one cycle of priority control in real time, the signal timings shall be recovered to its original plan so as to mitigate the impacts to other local traffic.
Conditional Priority Control

Conditional priority control strategy allows the presence of residual queue at the downstream links. Similar to the unconditional priority control strategy, the decision-making process includes the following steps:

**Step 1:** Collect the pre-timed signal plans at each involved intersection; and estimate the current queue length at the off-ramp intersection and its downstream intersections.

**Step 2:** Determine the acceptable length of residual queue at each intersection.

**Step 3:** Compute the green bandwidth for signal progression.

Compared with the unconditional priority control strategy, the conditional strategy offers variable green bands between intersections. Hence, the green bandwidths between neighboring intersections are given by:

\[ b_1 = \frac{q_1 - \varepsilon_i}{s} \]
\[ b_i = b_{i-1} - \varepsilon_i / s \]

Where \( \varepsilon_i \) is the allowable residual queue at intersection \( i \)
Step 4: Set the signal progression

*Step 4.1: Compute the extended green time $e_l$ and $e_r$:

$$e_l = \max\left(\frac{R_l (b_l - g_l)}{R_l + R_r} , 0\right)$$

$$e_r = \max\left(\frac{R_r (b_1 - g_1)}{R_l + R_r} , 0\right)$$
Conditional Priority Control

**Step 3.2:** Compute the green time $\overline{g}_i$ for the off-ramp path at intersection $i$;

In the conditional priority control strategy, the green time $\overline{g}_i$ at each intersection is given by:

$$\overline{g}_i = \max(b_i + \sum_{j=2}^{i} q_j/s, g_i)$$

**Step 3.3:** Compute the length of $w_i$:

$$w_2 = R_i - e_i + t_{1,2} - \theta_2$$

$$w_i = \theta_{i-1} - \theta_i + w_{i-1} + t_{i-1,i} - q_i/s; \quad i > 2$$

Also note that $\theta_i$ (offsets) could be a negative value.
Conditional Priority Control

**Step 5: Re-assign the green time to other phases at each intersection**

This step is the same as the one for unconditional priority control.

At each intersection, the remaining green time for each non-extended phase is computed by:

\[
g_j = g_j - \frac{g_j}{\sum_{\{k \in \delta, k \neq i\}} g_k} (g_i - g_i)
\]

where, \( \delta \) is the set of all phases; \( i \) is the index of extended (target) phase; \( g_j \) is the original green time of phase \( j \); \( \overline{g_j} \) is the re-assigned green time for phase \( j \).

**Step 6: Design the signal transition**

The design of signal transition is similar to the one for unconditional priority control.
Case Study for Real-time Control Strategy

To evaluate the proposed control system, one freeway segment in Zhubei, Taiwan along with its nearby intersections is selected as the study site.
Experimental Results

Based on the field observations, the major path for the off-ramp flows is from Node 4 to Node 10, as shown in Figure 8. Hence, the real-time priority control is designed to discharge the traffic along this path.

Also, to compare the network performance under different control strategies, three scenarios are tested in this study:

1) No control scenario: the signal timings are operated with the current fixed signal plans;

2) Unconditional priority scenario: only unconditional priority control strategy is implemented;

3) Dynamic control scenario: the decision-making function will dynamically switch to the proper strategy based on the detected traffic conditions.
Experimental Results

Following the control steps of each strategy, the real-time control frequency along with the assigned green band for off-ramp traffic is shown as follows:
Under both real time control strategies, the off-ramp queue didn’t spill back to the freeway mainline and bring negative effect to the mainline traffic, evidenced by the freeway travel time comparison between the three scenarios.
Experimental Results

**Evaluation of the critical traffic paths**

Travel time of path 4 → 10
(off-ramp traffic path)

The travel time from the off-ramp to the Zhubei area are significantly improved with the priority controls.

The travel times under dynamic control strategy (green line) are slightly higher than those with unconditional control (red line) since it produces a reduced green band when local streets are detected as congested.
Experimental Results

Evaluation of the critical traffic paths
Travel time of path 5→10

The travel time differences along this path under different control strategies are not significant.

One possible reason is that the path 5→10 has some shared link with the priority off-ramp path, and the clearance of queue at those shared links can also help reduce its travel time.
Experimental Results

*Evaluation of the critical traffic paths*  Travel time of path 8→9

The travel time of southbound through and left-turn movements are both significantly increased under the real-time control strategies.

Compared with unconditional control, the travel time performance under the dynamic control is much better since its conditional priority is applied after long queues are detected at 6:30 PM on important local segments.
Experimental Results

Evaluation of the critical traffic paths  Travel time of path 8–>2

The travel time of southbound through and left-turn movements are both significantly increased under the real-time control strategies.

Compared with unconditional control, the travel time performance under the dynamic control is much better since its conditional priority is applied after long queues are detected at 6:30 PM on important local segments.
## Experimental Results

### Entire network performance

<table>
<thead>
<tr>
<th>Performance Index</th>
<th>No Control</th>
<th>Unconditional Only</th>
<th>Dynamic Control Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average delay (s)</td>
<td>89.065</td>
<td>77.77 (-12.7%)</td>
<td>75.209 (-15.6%)</td>
</tr>
<tr>
<td>Average number of stops</td>
<td>2.391</td>
<td>1.711 (-28.4%)</td>
<td>1.621 (-32.2%)</td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>36.116</td>
<td>38.633 (7.0%)</td>
<td>39.25 (8.7%)</td>
</tr>
</tbody>
</table>
Thank you & Questions?