A Perimeter Control Strategy for Oversaturated Network Preventing Queue Spillback

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Abstract

A perimeter signal control strategy is investigated for a congested network. First, an algorithm is proposed to determine the proportion of traffic should be held outside during peak periods at each entry link, which is achieved by properly allocating green time for those movements. The optimization goal of this network control strategy is maximizing capacity utilization of the network, also preventing queue spillback. Lane-group-based method is used to model the traffic dynamics along arterials. Furthermore, the phase sequence and offset are optimized using an imbedded Genetic Algorithm. The signal timing outputs of this strategy are then implemented in TRANSYT-7F, and the results are compared with the outputs optimized through the TRANSYT-7F itself optimization process, which shows that the proposed strategy presents better performance, and more efficient for congested networks. The perimeter control strategy could be implemented for oversaturated networks to relieve the excessive congestion problems, particularly for those metropolitan in China.

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Keywords: traffic control, oversaturated network, queue spillback

1. Introduction

In the large cities of the developing world, travel times are generally high and increasing, and destinations accessible within limited time are decreasing. Urban central areas often fall to severe jam due

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to lack of capacity. Daganzo (2007) recently proposed that traffic can be modeled dynamically in large urban regions (neighborhoods) at an aggregate level if such regions exhibit two features: a reproducible “macroscopic fundamental diagram” (MFD) relating the number of circulating vehicles (or accumulation) to the neighborhood’s average speed (or flow), and a robust relation between the neighborhood’s average flow and its total outflow, if the neighborhoods are uniformly congested. Based on the MFD, he strongly suggests that systems susceptible to gridlock can be improved significantly by gently controlling their inputs. Perimeter control that restricts excess vehicles outside the congested area is proposed as a potential measure.

However, although control idea was proposed, Daganzo didn’t give feasible control strategies. Recently Abu-Lebdeh and Benekohal (1997) presented an algorithm for queue management and coordination of traffic signals along oversaturated arterials in primary direction. Girianna (2002) extended the previous algorithm to coordinate oversaturated signals along an arterial that crosses multiple, parallel coordinated arterials. Tang-Hsien Chang (2004) proposes a dynamic method to control an oversaturated traffic signal network by utilizing a bang-bang like model for the oversaturated intersections and TRANSYT-7F for the undersaturated intersections. An algorithm entitled the maximal progression possibility determines the optimal operating procedure by searching for progression routes and smoothing the transition between successive control cycles. Aboudolas (2010) formulated the problem of network-wide signal control (including all constraints) as a quadratic-programming problem that aims at minimizing and balancing the link queues so as to minimize the risk of queue spillback. However, these methods permit all traffic demand traveling into the network and passively evacuate queues after oversaturation occurs. The passive control strategies greatly restrict the control effect. Gal-Tzur (1993) proposed a method applying the ideas of metering to congested networks and adjusted them to the capacity of the critical intersections. This external metering prevents blockages from occurring. But the method was designed for small networks having only one critical intersection which have a smaller capacity than its demand.

Based on MFD, this paper presents a perimeter control strategy that prevents oversaturation from occurring for a large network with many critical intersections. Firstly, the control strategy would maximize the total throughput of the network. As the green durations allocated to each movement is often more important than the offset and phase sequences in oversaturated signalized network, an algorithm is designed to determine how many vehicles should be hold outside for each entry link and correspondingly the green durations allocated to each movement. Then, based on the pre-defined green durations, the offset and phase sequences would be optimized by GA to minimize the total network delays.

2. Control scheme

Strictly based on the MFD, Zhang Yong (2010) developed a Bang-Bang control strategy to optimize the accumulated vehicular number. However, because the MFD could be easily influenced by the signal settings (cycle length, splits, offsets and phase sequences) and other traffic management measures (Aboudolas, 2010), the accumulated vehicle numbers couldn’t be used as the control variables. Given a signalized network, if most intersections are saturated and no queuing overflow takes place, the network throughput would be maximal with no green times wasted. So, cycle length and green durations would be firstly optimized to make the network in partial saturation traffic conditions and maximize total network throughput. And then, offsets and phase sequences would be optimized to minimize total network travel time. Note that green durations of entry links are the control variables determining how many vehicles would be held outside. The control strategy is based on the assumptions that entry links are long enough to accommodate the vehicles held outside the network.
3. Throughput maximization

Normally, the signal timings are based on the volume on each link. When volumes are high enough that signal timing optimization is unable eliminate oversaturation, the green durations allocated to each movement is often more important than the offset and phase sequences. That is the offsets and phase sequences would have very little effect on network throughput (Hale, 2006).

Generally, pre-timed green durations are calculated by equalizing the degrees of saturation on conflicting critical movements and often determined by Eq. (1).

\[
g_{jp} = (C - T_l) \frac{Y_{jp}}{Y_j} \]

where \(g_{jp}\) is effective green time for phase \(p\) of intersection \(j\); \(C\) is cycle length in seconds; \(T_l\) is total lost time for the cycle in seconds; \(Y_{jp}\) is volume-to-saturation flow ratio for critical lane group of phase \(p\) and \(Y_j\) is the sum of volume-to-saturation flow ratio for critical lane groups of intersection \(j\).

As traditional minimum delay cycle length calculation method-Webster’s method is only effective for undersaturated, isolated intersections, different cycle length would be tested from minimum cycle length to maximum cycle length with predefined increment (e.g. 5s or 10s). The following algorithms in this section are all illustrated in a specific cycle length. The cycle length and correspondingly green durations with maximum total network throughput would be selected for further optimization.

In this paper, a lane-group-based macroscopic traffic flow formulations proposed by Liu (2011) is used to capture the traffic dynamics which can: (1) satisfy both computational efficiency and modeling accuracy; (2) represent the dynamic evolution of physical queues with respect to the signal status, arrivals, departures, and lane channelization; and (3) capture explicitly the dynamic interaction of queues among neighboring lanes and intersections experiencing spillback and blockage under congested traffic conditions.

3.1. Critical intersections identification

Generally, if the sum of volume-to-capacity ratios for critical lane groups is greater than 0.9 at a given intersection, the delay would increase exponentially, because some signal cycles will not have enough green time to serve the queue (Hale, 2006). This forces some vehicles to wait through multiple cycles before being served. The calculation of volume-to-capacity ratios requires the volumes. In uncongested networks, these volumes are simply the sum of the demand of all movements leading to a certain link. As the network becomes more congested and queues accumulate, the volume of certain links is determined by the green duration. In this case, the volume of the downstream intersection is not the demand but the throughput of upstream intersections. In other words, during congestion, volumes are sometimes determined by the throughput and green durations. But the green durations are optimized based on the volumes. This vicious circle can be solved by simultaneously determining the volumes and green durations (Gal-Tzur, 1993).

The following algorithm is designed to determine the initial traffic volumes and green durations simultaneously when cycle length is given. The traffic volumes would be the basis of the perimeter control to determine how many vehicles should be held outside. It is a kind of data cleaning. So, we call this algorithm the traffic volume cleaning algorithm (TVCA). The steps of TVCA are outlined as follows:

Step 0: Perform the lane-group-based macroscopic traffic flow formulation with green light stays on all the time to compute the traffic demands of lane groups. Here, the traffic demands are traffic volumes that potentially arrive at lane groups without blocking of upstream intersections. It would be used as start points \(Q^0 = \{Q^d_j; b \in \Gamma(j), l \in L_b\}, \Gamma(j)\) is the set of approach links of intersection \(j\) and \(L_b\) is the set of lane groups of link \(b\). Set \(n = 0\).
Step 1: For each intersection, based on $Q^0$, allocate green durations for each phase by equalizing its conflicting critical movements’ degrees of saturation (Eq. 1). Then calculate the each lane group’s capacity by multiplying green durations and saturation flows.

Step 2: Modify the lane-group-based macroscopic traffic flow formulations. For each lane group, if the accumulated traffic volume exceed its capacity, the surpass traffic volumes could depart from the links but wouldn’t travel into the downstream links. It acts as surpass traffic volumes disappear after they depart from the links. The motivation of this modification is to obtain the actual traffic volumes demanding to travel through each lane group. This model also considers the disturbance of queue spillback which will affect the capacity.

Step 3: Perform the modified lane-group-based macroscopic traffic flow formulations to compute the traffic volume $Q^{n+1}$ of each lane group.

Step 4: Convergence test. If $Q^{n+1} \equiv Q^n$, allocate green duration for each lane group by Eq. 1 and stop. Otherwise, set $n=n+1$ and go to step 1.

The results would be initial traffic volumes and green durations, which are the basis of the following optimization algorithms. If an intersection has smaller capacity than its demand (with the sum of volume-to-capacity ratios for critical lane groups less than 0.9), it is a critical intersection.

3.2. Green durations allocation

Assume the right-turn, left-turn and through traffic ratios of all approaches of each intersection are constants in the analysis period. The ratio of the vehicles generating from an entry link that arrives at a lane group can be determined. We call this ratio entry-to-lane group flow ratio (EL flow ratio). The ratios are important variables to calculate how many vehicles generating from each entry link should be held outside in the analysis period. With the development of Vehicle Infrastructure Integration (VII), more accurate EL flow ratio would be obtained by tracking or forecasting vehicles’ routes.

As illustrated before, to keep the critical intersections in near-saturation traffic condition, the sum of volume-to-capacity ratios for critical lane groups of these intersections should decrease to 0.9.

For each critical intersection, based on the criteria of equalizing the degrees of saturation on conflicting critical movements, the volume-to-capacity ratios of each phase should be decreased by:

$$Y_{j}^{p} = (Y_{j} - 0.9) \frac{Y_{j}^{p}}{Y_{j}}, j \in J, p \in P_{j}$$

where $P_{j}$ is the set of phases of intersection $j$.

Correspondingly, the traffic volume of each lane group needing to decrease is:

$$Q_{b}^{p} = \max(Y_{j}^{p} - (Y_{j} - Y_{j}^{p}), 0), b \in \Gamma(j), l \in L_{b}, p = \Lambda^{-1}(l)$$

where $p = \Lambda^{-1}(l)$ is the phase of intersection $j$ for lane group $l$, $Y_{j}^{p}$ is the volume-to-capacity ratio of phase $p$ needing to decrease to and $\max(Y_{j}^{p} - (Y_{j} - Y_{j}^{p}), 0)$ represents the decrement of the volume-to-capacity ratio for lane group $l$. If $Y_{j}^{p} < Y_{j} - Y_{j}^{p}$, the traffic volume of lane group $l$ needn’t decrease.

To prevent oversaturated from occurring, traffic demand of each entry link needing to be held outside could be computed by the following equation.

$$Q_{b}^{p} = \left( \frac{\sum_{i=1}^{q_{b}} R_{ib}^{p} Q_{b}^{p}}{\sum_{i=1}^{q_{b}} R_{ib}^{p}} \right) / R_{ib}^{p}, b \in \Gamma(j), l \in L_{b}$$

where $R_{ib}^{p}$ is the ratio of the vehicles generated from entry link $i$ that arrives at the lane group $l$ of link $b$.
and \(q_i R^l_{ib}\) is the number of vehicle generated from entry link \(i\). \(\sum_{i \in d} q_i R^l_{ib}\) represents the traffic volume of lane group \(l\) of link \(b\). Proportionally, we should prevent \((q_i R^l_{ib} Q^{id}_{b})/(\sum_{i \in d} q_i R^l_{ib})\) vehicles generated from entry link \(i\) from arriving at the lane group \(l\) of link \(b\). Obviously, to reach this goal, \((q_i R^l_{ib} Q^{id}_{b})/(\sum_{i \in d} q_i R^l_{ib})\) vehicles generated from entry link \(i\) should be held outside the network. We call it restricted demand as simple.

However, we could find that this value may be different for different lane groups \((Q^{id}_{b} \neq Q^{id}_{b})\). Which one should be selected? Obviously, if we want to avoid all intersections of the network to be oversaturated, we should select the maximum \((Q^{id}_{b}; b \in \Gamma(j), l \in L_b)\) ). However, two problems exist:

First, for other lane groups, traffic demands may be restricted excessively. The saturation degrees of those lane groups would be too low, thus the capacities would be partially wasted.

Secondly, according to Eq. (4), \(Q^{id}_{b}\) may be very large even when \(R^l_{ib}\) is small. For example, we assume \(R^l_{ib} = 0.01\), \(q_i = 300\), \(\sum_{i \in d} q_i R^l_{ib} = 1000\) and \(Q^{id}_{b} = 50\). Then 25 vehicles generated from entry link \(i\) should be held outside the network to prevent only 3 vehicles from arriving at the lane group \(l\) of link \(b\). It is so absurd.

To overcome these faults, the following algorithm is designed to determine how many vehicles arriving at each entry link should be held outside. This algorithm could not only maximize utilization of network capacities but also make sure there’s no risk of queue overflow of any intersection. The steps are as follows:

Step 0: Initialize. For each entry link, select the restricted demand of the lane group with maximal EL flow ratio as initial value \(Q^{d(0)}_i\). That is:
\[
Q^{d(0)}_i = Q^{id}_i, \text{ where } R^l_{ib} = \max \{R^l_{ib}, l \in L_b, b \in B\}.
\]
where \(B\) is the set of links of the network. Set \(n = 1\).

This step would exclude absurd larger \(Q^{id}_i\) with small \(R^l_{ib}\) and make a good starting point.

Step 1: Perform TVCA with permitted entry flow \(Q^p_i = q_i - Q^{d(0)}_i\) to compute the traffic volume of each lane group and the corresponding green durations. This step aims to generate traffic volumes if \(Q^{d(n)}_i (i \in I)\) vehicles are restricted.

Step 2: For intersections with the sum of volume-to-capacity ratios for critical lane groups larger than 0.9, compute their maximal queue length \(X^l_j \left( b \in \Gamma(j), l \in L_b, p \in \Lambda^d(l) \right)\) by run the lane-group macroscopic traffic flow model with green durations obtained from Step 1.

Step 3: If there are some queues lengths \(\{X^l_j\}\) (in vehs) exceed the choked lengths \(\{L^l_{ib}\}\) (in vehs), increase the restricted flow of all entry links by Eq. (6); else, go to Step 4.

\[
Q^{d(n+1)}_i = Q^{d(n)}_i + \left( X^l_j - L^l_{ib} \right) \sum_{i \in d} q_i R^l_{ib}.
\]
where \( l \) and \( b \) satisfy \( \bar{R}_{lb} = \max \{ R_{lb} \} \) and \( L_{lb}^{l,b} \) can be determined by the choked density and standard car length.

Step 4: If there are some intersections with the sum of volume-to-capacity ratios for critical lane groups less than 0.9, reduce the restricted flow of all entry links by Eq. 7; else, go to Step 5.

\[
Q_i^{l(x+1)} = Q_i^{l(n)} - \alpha l_i \sum_{q_i} q_i R_i^{l,b},
\]

where \( l \) and \( b \) satisfy \( \bar{R}_{lb} = \max \{ R_{lb} \} \) and \( \alpha \) is a pre-determined increment of queue length (e.g. 0.05 or 0.10).

Step 5: Convergence test. If \( Q_i^{l(x+1)} = Q_i^{l(n)} \), set \( n = n+1 \) and go to step 2; otherwise, perform TVCA with permitted entry flow \( Q_i^{e} = Q_i - Q_i^{l(x+1)} \) to gain the traffic volume of each movement and the corresponding green durations and terminate.

The outputs of the algorithm are green durations allocated to each movement. And the total network throughput will be computed by lane-group macroscopic traffic flow model with the green durations generated by the algorithm. As the degree of saturation of each lane group is near saturation, the network capacity would be maximally utilized. So, throughput is maximized.

4. Delays minimization

After the throughput is maximized by optimizing green duration, we would minimize the network delays (including vehicles already entering the network and vehicles waiting in the virtual queue at the demand entry) by optimizing offsets and phase sequences in this section. Given the time period \( T \) of analysis, the objective function is given by Eq. (8).

\[
\min \sum_{k=1}^{\Delta T} \left[ \sum_{i \in S} N_i[k] + \sum_{r \in S} w_r[k] \right] \cdot \Delta t
\]

where \( N_i[k] \) represents the number of vehicles on link \( i \) at time step \( k \) and \( w_r[k] \) means queue waiting on the entry \( r \) at step \( k \) (in vehs), they could be got from the macroscopic traffic flow formulations.

Only offsets and phase sequences would be optimized in this model. The proposed optimization model consists of complex formulations, including non-linear system constraints. It is thus difficult to find the global optimal solution through traditional non-linear integer programming approaches. So, GA-based heuristic of TRANSYT-7F(Hale, 2006) is used to yield efficient model solutions for signal settings.

5. Numerical tests

To demonstration the efficiency of the proposed approach to the problem of urban signal control in oversaturated road networks, results from the proposed approach is compared to TRANSYT-7F approach. The comparison was made for the same conditions including road environment, initial conditions, time slices, and simulation duration. Although TRANSYT-7F is commonly thought as signal timing optimization tool only for undersaturated conditions, it can address severely oversaturated conditions since release 8. Maximizing the throughput and minimizing the delay are selected as objective functions. All signal settings (cycle length, phase sequence, splits, and offsets) are optimized by genetic algorithm with step-wise simulation options selected. The optimized signal plans obtained from the proposed model will be simulated in TRANSYT-7F for an unbiased evaluation.
The hypothetical case network with 12 intersections and 66 links is illustrated in Fig. 1. It also depicts the length each segment in the core area. And the length of entry links and output links are all assumed to be 600m. Number of lanes for segments in north-south arterials and west-east arterials are set to be 2 and 3 respectively. The turning fractions for all intersection approaches are set to be 20% left-turn, 70% through, and 10% right turn. Table 1 depicts demands generating from entries.

5.1. Optimization model settings

The network flow model parameters are given below:
- The free flow speeds are set to be 40 km/h and the minimum speed is 6 km/h;
- Jam density is set to be 130.4 veh/km/lane and the minimum density is 12.4 veh/km/lane;
- An average length is set to be 7.62m; and
- The saturation flow of each link is set to be 1400 veh/h;

The GA optimization is performed with the following parameters:
- The population size is 30;
- The maximum number of generation is 100;
- The crossover probability is 0.5; and
- The mutation probability is 0.03.

5.2. Experiments results and analysis

After the data cleaning procedure, we can find that the sum of initial volume-to-capacity ratios of every intersection exceeds 0.9 (Table 1). Obviously, if all demand generated from entry links flow into the network, all intersections were possible oversaturated and some links may be overload.
Table 1. Sum of demand-to-capacity ratios for critical lane groups

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Sum of volume-to-capacity ratios</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.89</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.96</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.08</td>
<td>1.03</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.07</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.11</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.93</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.10</td>
<td>1.03</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1.01</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1.03</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.91</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.98</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.92</td>
<td>0.91</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Vehicle numbers need to be held outside the network at each entry link [Vehs]

<table>
<thead>
<tr>
<th>Entry</th>
<th>Flow restricted</th>
<th>Entry</th>
<th>Flow restricted</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>105</td>
<td>J</td>
<td>87</td>
</tr>
<tr>
<td>B</td>
<td>15</td>
<td>K</td>
<td>28</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>L</td>
<td>92</td>
</tr>
<tr>
<td>D</td>
<td>40</td>
<td>M</td>
<td>40</td>
</tr>
<tr>
<td>E</td>
<td>128</td>
<td>N</td>
<td>66</td>
</tr>
<tr>
<td>F</td>
<td>98</td>
<td>O</td>
<td>121</td>
</tr>
<tr>
<td>G</td>
<td>105</td>
<td>P</td>
<td>17</td>
</tr>
<tr>
<td>H</td>
<td>131</td>
<td>Q</td>
<td>15</td>
</tr>
<tr>
<td>I</td>
<td>121</td>
<td>R</td>
<td>48</td>
</tr>
</tbody>
</table>

Table 2 depicts the number of vehicles generated from each entry link to be held outside the network by perimeter control. And after the perimeter control, the sum of volume-to-capacity ratios of each intersection (Table 1) has a significant reduction. Further, referring to Table 3, all lane groups of links (except entry links) in the network are in near-saturation conditions with a degree of saturation near 1.0. The network capacity would be reached without queue spillback (with maximum queue-to-capacity ratio 0.65). The degrees of saturation of entry links’ lane groups are larger than 1.0 due to the demand restriction. We assume here that all entry links are long enough to accommodate all these vehicles. Generally, in the urban network, entry links may be middle sections of some roads. Traffic signal timings at upstream intersections should be adjusted to avoid entry links overload and store queues on upstream links.
Table 3. Degree of saturation of TRANSYT-7F and proposed model

<table>
<thead>
<tr>
<th>Node</th>
<th>EB</th>
<th>WB</th>
<th>NB</th>
<th>SB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TR</td>
<td>L</td>
<td>TR</td>
<td>L</td>
</tr>
<tr>
<td>1</td>
<td>1.14</td>
<td>1.07</td>
<td>1.03</td>
<td>1.03</td>
</tr>
<tr>
<td>2</td>
<td>1.13</td>
<td>0.97</td>
<td>1.06</td>
<td>0.82</td>
</tr>
<tr>
<td>3</td>
<td>1.04</td>
<td>1.06</td>
<td>1.02</td>
<td>1.02</td>
</tr>
<tr>
<td>4</td>
<td>0.78</td>
<td>0.94</td>
<td>0.81</td>
<td>0.96</td>
</tr>
<tr>
<td>5</td>
<td>0.61</td>
<td>0.84</td>
<td>0.66</td>
<td>0.96</td>
</tr>
<tr>
<td>6</td>
<td>1.10</td>
<td>1.05</td>
<td>1.14</td>
<td>1.03</td>
</tr>
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<td>0.95</td>
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<td>0.79</td>
<td>0.64</td>
<td>0.91</td>
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<td>10</td>
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<td>0.94</td>
<td>0.79</td>
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<tr>
<td>11</td>
<td>1.04</td>
<td>0.93</td>
<td>1.07</td>
<td>0.76</td>
</tr>
<tr>
<td>12</td>
<td>0.92</td>
<td>0.99</td>
<td>1.02</td>
<td>0.96</td>
</tr>
</tbody>
</table>

T: TRANSYT-7F, P: Proposed model.

Table 4. Comparison results from the proposed model and TRANSYT-7F

<table>
<thead>
<tr>
<th></th>
<th>Average Delay [s/veh]</th>
<th>Total Throughput [veh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed model</td>
<td>169.1</td>
<td>14410</td>
</tr>
<tr>
<td>TRANSYT-7F</td>
<td>204.4</td>
<td>13520</td>
</tr>
<tr>
<td>Improvement (%)</td>
<td>-17.3%</td>
<td>6.6%</td>
</tr>
</tbody>
</table>

Table 4 shows the comparison results from the proposed model and TRANSYT-7F. Although the proposed model hold some vehicles outside the network, the total throughput has significant improve (6.6%). Meanwhile, the average delay (including the vehicles held outside) decreases from 204.4s/veh to 169.1s/veh.

6. Conclusions

This study proposed a perimeter control method for oversaturated networks which held the demand exceed intersection capacity outside the network to keep most intersections in near-saturation traffic conditions. The network throughput would be maximized and there is no risk of queue spillback. Furthermore, the phase sequence and offset were optimized by GA to minimize the network delay. Numerical results show the proposed method performed well than TRANSYT-7F in oversaturated network. Almost all lane groups of links in the network are in near-saturation conditions with a degree of saturation near 1.0. The network capacity is fully used and the network throughput and delay are greatly improved.

Note, although the approach proposed is a fixed signal timing method, it could be easily integrated with the rolling time horizon to adapt to dynamic traffic.
References


