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Optimizing Signal Timing at Multiple Intersections under Oversaturation Conditions

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Abstract: In transportation networks, traffic conditions are often in an oversaturated state. In this case, by coordinating the signal timing at multiple intersections to improve the significant road bottleneck capacity is necessary. Urban roads have entry capacity and exit capacity affected by the signal timing at intersections and properties of left-turn lanes and straight lanes of roads. With the help of the discrete-time model, road entry capacity and exit capacity are formulated, and then the bottleneck road capacity under oversaturation conditions can be determined. Based on which, the objective function is to improve the significant bottleneck capacities and throughput of vehicles entering and leaving a special transportation network by using effective green times at multiple intersections as the decision variables, through applying the Ant Colony Algorithm to find an optimal signal-timing plan. The results of numerical example indicate this approach to optimizing the signal timing of multiple intersections is feasible and effective.

Keywords: discrete-time model; road bottleneck capacity; signal coordination; Ant Colony Algorithm; traffic congestion;

1 Introduction

In urban transportation networks, traffic conditions are often in an oversaturated state, which refers to the situation that ration of traffic volume and capacity is greater than 1.0 [1]. Many factors can lead to the urban roads in an oversaturated state. During rush hours, traffic demand is great enough to cause oversaturated traffic flows on urban roads. Besides, some fixed static bottlenecks can play their roles, such as the poor road alignment, the road width narrowing, on-ramps, off-ramps, which can affect the road capacity analyzed in [2,3,4], and even some of network topologies [5]. Furthermore, some bottlenecks and their influence are relatively implied, such as moving bottlenecks caused by slow vehicles [6], bottleneck queuing congestion due to the step tolling schemes [7], etc.

The oversaturated flows are frequently accompanied with traffic congestion and traffic accidents [8]. The commonly used traffic control such as HCM(Highway Capacity Manual) [9], SCOOT, can not work efficently so as to treat in a different way [10]. Hence, the special optimal meausres for the oversaturation conditions are required to improve bottleneck capacities widely existed in the transportation network and to manage traffic demand are essential. Tao Yao et al. gave a class of financial derivatives based on congestion in a decision environment, which had the potential to reduce traffic volume by altering drivers' departure behavior [11]. While F. Siebel et al. presented a method to balance vehicular traffic at bottlenecks like on-ramps and off-ramps [12]. Zhang et al.found that ramp metering can increase the bottleneck capacity by postponing and sometimes eliminating bottleneck activations, accommodating higher flows during the pre-queue transition period [13]. Traffic congestion propogating upstream can greatly reduce the traffic capacities, so Kerner proposed a methodology for preventing wide moving jams from propagating continuously upstream according to the three-phase traffic theory[14,15,16].

Signal control at intersections for managing traffic is also received many attentions. It can adjust bottleneck road capacity [17,18], dissipate queues, remove blockages, mitigate traffic congestion, reduce the vehicular delay and improve traffic fluency between adjacent intersections. Coordinating signal control at multiple intersections instead of an isolated intersection [19] has gradually prevailed. In this respect, the optimal measures are diverse due to a variety of objectives, such as maximizing system throughput, fully useing storage

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capacity, providing equitable service [20],considering total queue vehicle number and the total output vehicle number of regional intersection [21]. The methods involved are data-driven [22] and heuristic algorithms like Ant Colony Algorithm and Genetic Algorithm [23].

Signal control at intersections also has side effects on causing oversaturated traffic flows. Guido Gentile et al.regarded road entry and road exit capacities as time-varying bottlenecks to represent the formation and dispersion and propagation of vehicle queues on road links[24]. In the same way, we can address the state of oversaturated flows occurred on roads. The road entry capacities are related with the signal timing at upstream intersections, the road exit capacities with the signal timing at downstream intersections. Especially under oversaturation conditions, traffic entry volume and exit volume are in proportion to the length of effective green time. Hence, signal timing at the ends of a road can play roles in determining bottleneck capacities of roads. When the signal timing at a intersection is adjusted, the influence will spread over all the roads adjacent to the intersection, and the adjacent intersections. Therefore, optimization of signal timing at a intersection is required to coordinate with other intections.

The contributions of this work are two heads. One is to define the bottleneck capacity of roads through regarding road entry and road exit capacities as time-varying bottlenecks affected by the traffic light. Based on which, an approach to improving the bottleneck capacities by coordinating the signal timing at multiple intersections in a network are proposed under the oversaturation conditions.

2 Model formulation

2.1 model assumptions

An urban transportation network is the couple

UTN={I,R},

Where I ={I_s,s=1,...,S} is the set which gathers the S signalized intersections in the transportation network, R={R_m,m=1,...,M} is the set which gathers the M roads.

Road α is a generic urban road linking two signalized intersections, as shown in Fig.1. The main symbols are shown as follows.

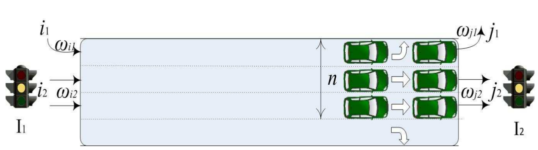

Fig. 1: Road α with two signalized intersections

(1)I_1(I_2):upstream (downstream) signalized intersection of road α , $I_1 \in$I, $I_2 \in$I

(2)i_1(i_2):left-turn (straight-through) entry flows at intersection I_1

(3)j_1(j_2):left-turn (straight-through) exit flows at intersection I_2

(4)n: total of the numbers of left-turn exit lanes and straight exit lanes of road α.

(5)$\omega_{i1}, \omega_{i2}, \omega_{j1}, \omega_{j2}$:$\omega_{i1}$ and ω_{i2} are the numbers of left-turn lanes and straight lanes of upstream roads of road α, which are equal to the numbers of traffic flows i_1 and flows i_2 respectively. ω_{j1} and ω_{j2} are the numbers of left-turn lanes and straight lanes of road α, which are equal to the numbers of traffic flows j_1 and flows j_2 respectively.

Flows i_1 and flows i_2 are controlled by the traffic light at intersection I_1, flows j_1 and flows j_2 controlled by the traffic light at intersection I_2. The right-turn entry traffic flows and right-turn exit traffic flows are regardless of due to the reason that the traffic light at intersections I_1& I_2 do not control them. In addition, we also assume the entry flows and exit flows are oversaturated, so that the traffic volumes are in proportion to the length of effective green time.

Intersections I_1& I_2 can chose a variety of traffic light control, such as two-phase signal control, three-phase signal control, four-phase signal control, etc, as shown in Fig.2. A couple of signal control at intersections I_1& I_2 make up a signal-timing plan.

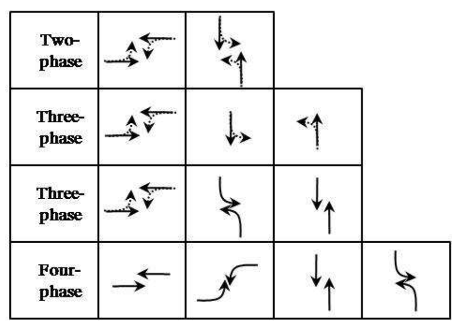

Fig. 2: Four typical signal control

To depict the signal timing, parameters used are as follows

(1)cl: the cycle length

(2)Green split λ(0< λ <1): ratio of effective green time of the phase that controls flows j_1 and flows j_2 synchronously to the cycle length

(3)$1/\gamma$ (0< $1/\gamma$ <1): ratio of the total of the effective green time of the phases that control flows i_1 or flows i_2 asynchronously to the cycle length

(4)$1/\mu$ (0< $1/\mu$ <1): ratio of the total of the effective green time of the phases that control flows j_1 or flows j_2 asynchronously to the cycle length

(5)η: ratio of the effective green time of the phase that controls the flows i_1 to the effective green time of the phase that controls the flows i_2

(6)φ: ratio of the effective green time of the phase that controls the flows j_1 to the effective green time of the phase that controls the flows j_2

2.2 entry capacities related with the signal timing at intersection I_1

To establish the relationship between the entry capacities and the signal timing, we can choose the discrete-time method to analyze.

Let π denote the entire analysis period, which can be divided into intervals of length δ [25], and $\pi >> \delta$. These intervals are numbered 0, 1, 2. The kth interval corresponds to [kδ,(k+1)δ). Let λ_1(k) (λ_2(k)) represents ratio of effective green time of the phase that controls flows $i_1(i_2)$ to δ at interval k respectively.

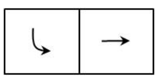

Fig. 3: time sequence of traffic flow entering road α

Fig.3 shows the time sequence of traffic flow entering road α no matter what type of signal control is chosen at intersection I$_1$, so at interval k , the entry oversaturation traffic volume $u'_a(k)$ can be expressed as

$$u'_a(k) = [\lambda_1(k)\omega_{i1} + \lambda_2(k)\omega_{i2}]q \quad (1)$$

With q as maximum number of vehicles per lane entering road α or leaving road α in interval of δ.

The entire analysis period π can be expressed as (k_1, k_t=[π/δ]) and the number of vehicles entering road α can be approximately computed like

$$\sum_{k=1}^{k=k_t} u'_a(k) = (\sum_{k=1}^{k=k_t} \lambda_1(k)\omega_{i1} + \sum_{k=1}^{k=k_t} \lambda_2(k)\omega_{i2})q \quad (2)$$

When two-phase signal control is chosen at intersection I$_1$, there is a relationship like

$$\sum_{k=1}^{k=k_t} \lambda_1(k) + \sum_{k=1}^{k=k_t} \lambda_2(k) = \frac{\pi}{\delta} \quad (3)$$

$$\sum_{k=1}^{k=k_t} \lambda_1(k) = \eta \sum_{k=1}^{k=k_t} \lambda_2(k) \quad (4)$$

Consider (1)-(4), equation (2) can be equivalently rewritten as

$$\sum_{k=1}^{k=k_t} u'_a(k) = [\frac{\eta\omega_{i1} + \omega_{i2}}{(\eta+1)}]\pi q/\delta \quad (5)$$

In terms of (5), equation (1) can be rewritten as

$$u'_a(k) = u_a = [\frac{\eta\omega_{i1} + \omega_{i2}}{(\eta+1)}]q \quad (6)$$

At any intervals, the value of $u'_a(k)$ is a constant and equal to u_a which is the sum of left-turn entry oversaturation traffic volume $q\eta\omega_{i1}/(\eta+1)$ and straight-through entry oversaturation traffic volume $q\eta\omega_{i2}/(\eta+1)$, hence u_a represents the entry capacity in interval of δ.

When a four-phase signal control is chosen at intersection I$_1$, there is a relationship like

$$\sum_{k=1}^{k=k_t} \lambda_1(k) + \sum_{k=1}^{k=k_t} \lambda_2(k) = \frac{\pi}{\gamma\delta} \quad (7)$$

Then, equation (8) can be obtained

$$u'_a(k) = u_a = [\frac{\eta\omega_{i1} + \omega_{i2}}{\gamma(\eta+1)}]q \quad (8)$$

When a two-phase signal control is chosen at intersection I$_1$, and all-red time during the period of cl is taken into account, equation (6) can be modified as equation (8).

2.3 exit capacities related with the signal timing at intersection I_2

At intersection I$_2$, time sequence of traffic flow leaving road α can be classified into two categories shown in Fig.4.

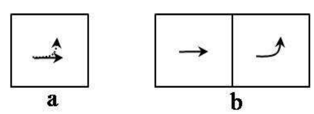

Fig. 4: time sequence of traffic flow leaving road α

Category a can appear in the two-phase signal control or three-phase signal control, Category b the three-phase signal control or four-phase signal control. Similarly, at interval k, when category a is selected, the exit oversaturation traffic volume $z'_a(k)$ can be expressed as

$$z'_a(k) = z_a = \lambda nq \quad (9)$$

At any interval, the value of $z'_a(k)$ is a constant equal to z_a which is the sum of left-turn exit oversaturation traffic volume $\lambda q\omega_{j1}$ and straight-through exit oversaturation traffic volume $\lambda q\omega_{j2}$, hence z_a represents the exit capacity in interval of δ.

When category b is selected, at interval k, the exit oversaturation traffic volume $z'_a(k)$ can be expressed as

$$z'_a(k) = z_a = [\frac{\varphi\omega_{j1} + \omega_{j2}}{\mu(\varphi+1)}]q \quad (10)$$

At any interval, the value of $z'_a(k)$ is a constant equal to z_a which is the sum of left-turn exit oversaturation traffic volume $q\varphi\omega_{j1}/\mu(\varphi+1)$ and straight-through exit oversaturation traffic volume $q\varphi\omega_{j2}/\mu(\varphi+1)$, hence z_a represents the exit capacity in interval of δ.

2.4 determination of road bottleneck capacity

Bottleneck capacity of road α denoted by c_a is determined by

$$c_a = min(u_a, z_a) \quad (11)$$

Under the condition of $c_a = z_a$, road α is a traffic bottleneck. Once the entry traffic volume is greater than the value of z_a, the accumulation of vehicles on road α can occur.

Under the condition of $u_a = z_a$, road α is in a critical state.

Under the condition of $c_a = u_a$, road α is a bottleneck-free road. In this case, road α has the potential to dissipate the congested vehicles through the signal scheduling.

From (6),(8),(9),(10) and (11), we can know the values of signal timing parameters (i.e.,$\eta, \varphi, 1/\gamma, 1/\mu, \lambda$) virtually determine the road bottleneck capacity c_a.

If road α is a traffic bottleneck and accumulation of vehicles has occur, adjusting the values of signal timing parameters for making the condition of $c_a = u_a$ met can change a bottleneck road into a bottleneck-free road. As a result, accumulated vehicles can dissipate. Even though the condition of $c_a = z_a$ still met, increasing value of z_a means the increase of the road bottleneck capacity.

Consider the influences coming from the upstream roads, equation (11) can also be rewritten as

$$c_a = min(c_b * l + c_d * d, z_a) \quad (12)$$

Where c_b, c_d are road bottleneck capacities of upstream roads of road α, and left-turn entry traffic flows come from road b, straight-through entry traffic flows from road d. l is the ratio of left-turn saturation volume, d is the ration of straight-through saturation volume.

3 Optimization approaches

3.1 The optimization objective

In practice, it is impossible to alter signal timing for a single road. Adjustment of signal timing at an intersection is required to take into account its action for all the adjacent roads, even to coordinate with other intersections.

The optimization objective oriented to multiple intersections is to find an overall signal timing plan to maximize the number of leaving vehicles on outgoing roads under the oversaturation traffic conditions. Then, four vectors are considered.

(1)C=(c_1,...,c_z),c_z=G(η_{s1},φ_{s2},$1/\gamma_{s1}$,$1/\mu_{s2}$,λ_{s2}), Function G can refer to (6),(8),(9),(10),(11), where c_z is the bottleneck capacity of roads where traffic flows leave the network.

(2)Vector of effective green time T=(T_1,...,T_s), T_s is the total of initial effective green time of phases of each signalized intersection.

(3)Vector of phases P=(P_1,...,P_s), P_s=(p_{s1}, p_{s2},,, p_{sv}),v$\in\{2,3,4\}$.

(4)Use effective green times at multiple intersections as the decision variables, i.e., a vector $\zeta=(\zeta_1=(g_{11},g_{12},,, g_{1v}),...,\zeta_s=(g_{S1},g_{S2},,, g_{Sv}))$ representing a signal timing plan, g_{Sv} is the length of effective green time of phase p_{sv} , to satisfy :

$$max(F(\zeta) = \sum_{t=1}^{t=z} c_t) \quad (13)$$

$$s.t. \sum_{t=1}^{t=v} g_{st} = T_s, g_{st} \in [LOWTOP] \quad (14)$$

Where $F(\zeta)$ is an objective function on maximizing the road capacities of roads on which traffic flows leave the network, which is not a convex function. Equation (14) is a constraint condition, which indicates the total length of effective green time of phases at an intersection keep constant. In addition, the length of effective green time of individual phase at a intersection vary only in a range[LOW,TOP].

3.2 Algorithm

To search ζ, a heuristic algorithm like Ant Colony Algorithm is adopted. The steps in the algorithm are:

Step 1: Initialization.

Step 1.1:Perform the network loading, including intersections, roads (properties of intersections linked to,ω_{j1},ω_{j2}, and$n$), phases at intersections(initial signal timing of individual phase, type of phase, traffic flows controlled, intersection affiliated to). Update ω_{i1} and ω_{i2} of the road according to the $\omega_{j1}$and ω_{j2} of its upstream roads respectively.

Step 1.2:Constant Setting, such as ANTS(number of ants),TIMES(number of ants' moving times), RPE (rate of pheromone evaporation),PST(probability of state transitions),LR(radius of local search), GR(radius of global search).

Step 2:Compute $F_t(\zeta)$.

Step2.1: Under the constraint condition of (14), conduct a stochastic global search. $\zeta = \zeta^{\Lambda} + \zeta^{\Omega}$, where$\zeta^{\Lambda}$ is a vector which represents the initial length of effective green time. ζ^{Ω} is a vector with the global stochastic radius of length of effective green time.

Step 2.2: Compute $F_t(\zeta)$ for each ant by (6),(8),(9),(10),(11),(12), (13).

Step3: Search the optimal ζ.

Step3.1: If traversal times are greater than TIMES, go to Step4.

Step3.2: Compute probabilities of state transition for each ant according to

$$\rho(t) = 1 - F_t(\zeta)/max(F_1(\zeta),..,F_t(\zeta),..) \qquad (15)$$

Step3.3: Under the condition of (14), if ρ(t)<PST, conduct a local search of the length of effective green time; otherwise, conduct a global search.

Step3.4:Compute $F_t^{\Lambda}(\zeta+\zeta^{\Omega})$ by (6),(8),(9),(10),(11),(12),(13), if $F_t^{\Lambda}(\zeta+\zeta^{\Omega}) > F_t(\zeta)$, let $\zeta=\zeta+\zeta^{\Omega}$.

Step3.5:Update the amount of pheromone according to

$$F_t(\zeta) = (1-RPE) * F_t(\zeta) + F_t^{\Lambda}(\zeta) \qquad (16)$$

Step3.6: t=t+1,IF t<ANTS goto step3.2.

Step3.7: Goto step3.1.

Step4: Output ζ and C.

4 Numerical example

Consider a simple network reported in Fig.5, which consists of five signalized intersections(I_1, I_2, I_3, I_4, I_5) with four incoming directions (roads), namely, R_1,R_2,R_3,R_4, represented the roads on which traffic flows enter the network, and four outgoing directions(roads), namely, R_5,R_6,R_7,R_8, represented the roads on which traffic flows leave the network.

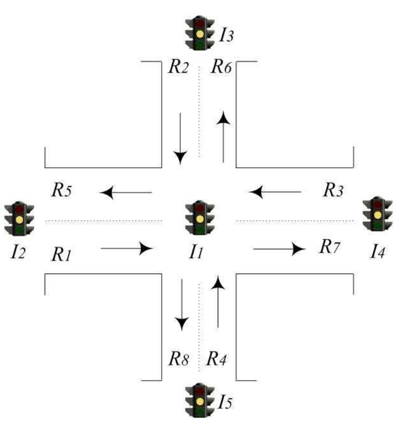

Fig. 5: A simple network with five signalized intersections

For simplicity sake, All the intersections chose two-phase control as shown in Fig.6, and all the initial signal timing of phases are set to be (60, 60), which indicates the effective green time of 60sec, the red time of 60sec, without all-red time.

The relative parameters are: ANTS=200, TIMES=100, RPE=0.98, PST=0.02, LR=2, GR=10, T=(120,120,120,120,120), δ=30sec, q=10veh, π=3600sec.

Table 1: Properties of roads.

Road	ω_{i1}	ω_{i2}	ω_{j1}	ω_{j2}	n
R_1	1	3	1	3	4
R_2	1	2	1	2	3
R_3	1	3	1	3	4
R_4	1	2	1	2	3
R_5	1	3	1	3	4
R_6	1	2	1	2	3
R_7	1	3	1	3	4
R_8	1	2	1	2	3

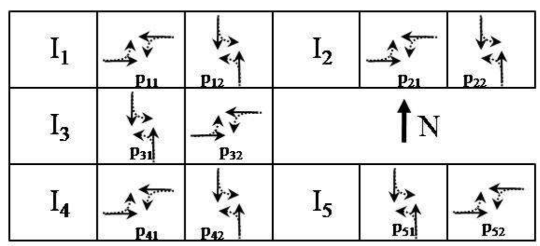

Fig. 6: Phase sequence at Intersection I_1, I_2, I_3, I_4, I_5

The properties of roads in the test network are shown in Table.1.

Note the fact that some roads adjacent to intersection I_2, I_3, I_4, I_5 are not the parts of the test network, which means the less influences of left-turn traffic flows on these roads entering the network are considered in the process of searching optimal signal timing plan. Thus, we impose a restriction that the lengths of effective green time of phases that control traffic flows leaving the test network vary in the range [50, 70].

Table.2 lists six groups of results. The first is the result before optimizing, while the others are the optimized results. The optimized results indicate that there are multiple optimal signal timing plans ζ, which are likely to correspond to the same C. In addition, much more effective green time at multiple intersections is assigned to East-west directions, namely R_1,R_5,R_3,R_7, the bottleneck capacities of which are significant to the network, because the roads in these directions have more lanes which have potential to improve throughput of vehicles promptly.

Table 2: results before and after optimizing.

NO	ζ	$C=(c_5,c_6,c_7,c_8)$
1	(60,60,60, 60,60, 60,60 ,60,60,60)	(2400,1800,2400,1800)
2	(70,50, 66, 54,59, 61,66 ,54, 64,56)	(2600,1700,2600,1700)
3	(69,51,66, 54,61, 59,68 ,52, 69,51)	(2580,1710,2580,1710)
4	(70,50,65, 55,66, 54,65 ,55, 70,50)	(2600,1700,2600,1700)
5	(65,55,65, 55,66, 54,65 ,55, 69,51)	(2500,1750,2500,1750)
6	(70,50,68, 52,63, 57,70 ,50, 70,50)	(2600,1700,2600,1700)

5 Conclusions

In urban transportation networks, signal timing at intersections together with properties of left-turn lanes and straight lanes of roads are two of significant factors in affecting the road bottleneck capacity, which can be determined according to the entry capacity and exit capacity. Based on which, the objective function is to improve the significant road bottleneck capacities and throughput of vehicles entering and leaving a special transportation network by using effective green times at multiple intersections as the decision variables, through applying the Ant Colony Algorithm to find an optimal signal-timing plan. The results of numerical example indicate this approach to coordinate the signal timing of multiple intersections is feasible and effective. However, this approach is on the assumptions that the transportation network should be in an oversaturation state and right-turn traffic is regardless. Therefore, this approach is appropriate for analyzing the coordination of signal timing at intersections during rush hours, and the effects of right-turn flows on the traffic conditions through comparative analysis.

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