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Identification and optimization of traffic bottleneck with signal timing

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Abstract: In urban transportation network, traffic congestion is likely to occur at traffic bottlenecks. The signal timing at intersections together with static properties of left-turn and straight-through lanes of roads are two significant factors causing traffic bottlenecks. A discrete-time model of traffic bottleneck is hence developed to analyze these two factors, and a bottleneck indicator is introduced to estimate the comprehensive bottleneck degree of individual road in regional transportation networks universally, the identification approaches are presented to identify traffic bottlenecks, bottleneck-free roads, and bottleneck-prone roads. Based on above work, the optimization method applies ant colony algorithm with effective green time as decision variables to find out an optimal coordinated signal timing plan for a regional network. In addition, a real experimental transportation network is chosen to verify the validation of bottleneck identification. The bottleneck identification approaches can explain the features of occurrence and dissipation of traffic congestion in a certain extent, and the bottleneck optimization method provides a new way to coordinate signal timing at intersections to mitigate traffic congestion.

Key words: traffic bottleneck; bottleneck indicator; signal timing coordination; ant colony algorithm; discrete-time model

1 Introduction

In urban transportation network, traffic congestion is likely to occur at some locations, which are called traffic bottlenecks (Wright and Roberg 1998), and that may account for 40% of significant factors causing traffic congestion(US Department of Transportation 2006).

Some fixed static bottlenecks are well known, such as the poor road alignment, the road width narrowing, on-ramps, off-ramps, and even some of network topologies(Sun et al. 2014). Bottlenecks can affect the road capacity (Chung et al. 2007; Guumlnther et al. 2012; Tang et al. 2012). Some control strategies were given for traffic bottlenecks, such as balancing vehicular traffic (Siebela et al.

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2009), preventing wide moving jams from propagating continuously upstream according to three-phase traffic theory (Kerner 2005, 2008), mitigating freeway traffic congestion by reinforcement of learning ramp metering (RLRM) control method (Wang et al. 2012), and introducing traffic signal to control traffic flows and improve bottleneck capacity (Lo and Chow 2004; Zhao and Gao 2006; Li et al. 2007; Li et al. 2013).

However, some bottlenecks and their influences are relatively obscure and they need further analysis. Leclercq (2007) proposed an extension of LWR model to describe the effect of road section reductions and the influence of slow-moving vehicles (such as buses) representing as moving bottlenecks, so that traffic operation strategies could be evaluated. Juran et al. (2009) developed a dynamic traffic assignment model to evaluate the effects of moving bottlenecks on network performance, which defined a situation that a slow-moving vehicle disrupted the continuous flow of general traffic. Coifman and Kim (2011) noted that freeway bottlenecks appeared to occur over an extended distance and developed a theory to explain the underlying mechanism. Gentile et al. (2007) took road entry and road exit capacities as time-varying bottlenecks to represent the formation, dispersion, and propagation of vehicle queues on road links. Zheng et al. (2011) located active bottlenecks by wavelet-based energy using loop detector data from a freeway, and analyzed important features of bottleneck activations in congested traffic systematically. Kerner (2011) presented a network breakdown minimization principle to minimize probability of congestion occurrence in the whole network, which was much more applicable for real traffic networks that were far from equilibrium and stationary compared with Wardrop′s principles. Robin and Vincent (2012) found the bottleneck queuing congestion was due to the toll schemes, because drivers would slow down or stop just before reaching a toll station and wait until the toll is lowered from one step to the next step, so an optimal tolling scheme should be proposed to prevent or limit drivers′ braking. Yao et al. (2010) gave the financial derivatives for congestion in a decision environment with active bottlenecks, which could reduce total social cost by altering drivers′ departure behavior and reducing drivers′ risks of high variance of trip costs. Zhang and Levinson (2010) proposed a methodology to systematically identify active freeway bottlenecks in a metropolitan area. It is 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, and increasing queue discharge flow rates after breakdown.

Besides the above-mentioned bottlenecks, roads under certain circumstances frequently act as traffic bottleneck. With the traffic volume increasing, some roads have blocked and others not, some are prone to congesting while others not. It is obvious that bottlenecks are related with signal timing and traffic flow volume. Hence, it will be very helpful to find an approach to identify such traffic bottlenecks and find optimization approaches to coordinate signal timing at intersections. In fact, there are various optimization approaches with diverse motives, such as network decomposition (Lieberman and Chang 2005), managing oversaturation traffic flows (Hu et al. 2011), minimum delay and better traffic fluency between adjacent intersections (Chin et al. 2011), dissipation of queues and removal of blockages (Putha et al. 2012), and adjustment of road capacity (Ma et al. 2013).

There are two contributions of this work. One is to propose approaches of identifying traffic bottle roads, bottleneck-prone roads in urban transportation network with two factors, signal timing at intersections and properties of left-turn lanes and straight-through lanes of roads. The other is to propose an approach to reduce impacts of traffic congestion arising from traffic bottlenecks by signal timing at intersections in a regional network.

2 Model formulation

2.1 Research objective

An urban transportation network is described as

$$UTN = \{I, R\}$$

where $I = \{I_s, s = 1, \cdots, S\}$ is the set which gathers the S signalized intersections in the network; $R = \{R_m, m = 1, \cdots, M\}$ is the set which gathers the M roads in the urban area, each R_m can also be denoted by I_{s1} I_{s2} ($I_{s1} \in I$, I_{s1} is an upstream intersection of R_m, $I_{s2} \in I$, I_{s2} is a downstream intersection of R_m) .

The research objective of traffic bottlenecks in an urban transportation network is to discover the spatial and temporal regular factors capable of accumulating or dissipating vehicles on roads. The signal timing at intersections and properties of left-turn lanes and straight-through lanes of roads are then taken into account, regardless of some stochastic dynamic factors such as traffic accidents and right-turn entry (exit) traffic flows not controlled by the traffic light.

Figure 1 shows a typical urban road α which links to two signalized intersections. The main symbols are shown in Tab. 1.

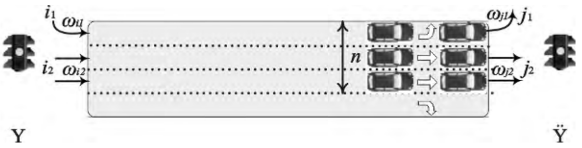

Fig. 1 Road α with two signalized intersections

Tab. 1 Symbols of road α in Fig. 1

Symbol	Meaning
Y(Ÿ)	Upstream (downstream) signalized intersection of road α, Y $\in I$, Ÿ $\in I$
i_1(i_2)	Left-turn (straight-through) entry flows at intersection Y
j_1(j_2)	Left-turn (straight-through) exit flows at intersection Ÿ
n	Total numbers of left-turn exit lanes and straight-through exit lanes of road α
ω_{i1}, ω_{i2}	Numbers of left-turn lanes and straight-through lanes of upstream roads of road α, respectively
ω_{j1}, ω_{j2}	Numbers of left-turn lanes and straight-through lanes of road α, respectively

At intersection Y, flows i_1 and i_2 are controlled not only by the traffic light, but also by the static properties of left-turn lanes and straight-through lanes of upstream road. At intersection Ÿ, flows j_1 and j_2 are controlled not only by the traffic light, but also by the static properties of left-turn lanes and straight-through lanes of road α. Therefore, the accumulation or dissipation of vehicles on road α are affected by the signal timing at intersections Y and Ÿ, and properties of road α and its upstream roads.

2.2 Signal timing plans versus bottleneck roads

The entire analysis period is divided into intervals with length δ (Chabini et al. 2001) . These intervals are numbered by 0, 1, 2. The kth interval is described as ($k\delta$, ($k+1$) δ) . The discrete-time variables are shown in Tab. 2.

Tab. 2 Discrete-time variables

Symbol	Meaning
$\lambda_1(k)$ ($\lambda_2(k)$)	Ratio of effective green time of the phase that controls flows i_1(i_2) to δ at interval k respectively
$\lambda_3(k)$ ($\lambda_4(k)$)	Ratio of effective green time of the phase that controls flows j_1(j_2) to δ at interval k respectively if intersection Ÿ chooses a four-phase signal control
$\lambda_5(k)$	Ratio of effective green time of the phase that controls both flows j_1 and flows j_2 to δ at interval k if intersection Ÿ chooses a two-phase signal control
$u_a'(k)$	Entry saturation flow volume at interval k
$z_a'(k)$	Exit saturation flow volume at interval k

At interval k, $u_a'(k)$ can be expressed as

$$u_a'(k) = [\lambda_1(k)\omega_{i1} + \lambda_2(k)\omega_{i2}] C_a \tag{1}$$

where C_a is maximum number of vehicles per lane entering road α or leaving road α at interval of δ.

Intersections Y and Ÿ can choose a variety of traffic light controls, such as two-phase signal control, three-phase signal control, four-phase signal control, or five-phase signal control. A couple of signal controls at intersections Y and Ÿ make up a signal timing plan. Here, two-phase control and four-phase control as shown in Fig. 2 are used in study to analyze.

The parameters related with signal timing are shown in Tab. 3.

In terms of signal control types, there are four categories as follows.

(1) Y and Ÿ: two-phase controls (signal timing plan Y2Ÿ2)

The value of $z_a'(k)$ can be defined as

$$z_a'(k) = \lambda_5(k) n C_a \tag{2}$$

According to Eqs. (1) and (2) , the number of increased vehicles on road α at interval k can be computed as

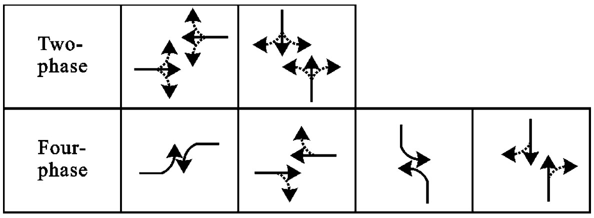

Fig. 2 Two types of signal control used in the model

Tab. 3 Signal timing parameters

Symbol	Meaning
λ	$0<\lambda<1$, ratio of effective green time of the phase that controls flows j_1 and j_2 synchronously to cycle length
$1/\gamma$	$0<1/\gamma<1$, ratio of total effective green time of the phases that control flows i_1 or i_2 asynchronously to cycle length
$1/\mu$	$0<1/\mu<1$, ratio of total effective green time of the phases that control flows j_1 or flows j_2 asynchronously to cycle length
η	Ratio of effective green time of the phase that controls flows i_1 to effective green time of the phase that controls flows i_2
φ	Ratio of effective green time of the phase that controls flows j_1 to effective green time of the phase that controls flows j_2

$$u_a'(k) - z_a'(k) = [\lambda_1(k)\omega_{i1} + \lambda_2(k)\omega_{i2} - \lambda_5(k)n]C_a \qquad (3)$$

Let π_a represent the least common multiple of two signal cycle lengths at intersections Y and Ÿ. The number of increased vehicles in interval of $\pi_a(k_t, k_t' = k_t + (\pi_a/\delta))$ can be approximately computed as

$$\sum_{k=k_t}^{k_t'}[u_a'(k) - z_a'(k)] = [\sum_{k=k_t}^{k_t'}\lambda_1(k)\omega_{i1} + \sum_{k=k_t}^{k_t'}\lambda_2(k)\omega_{i2}) - \sum_{k=k_t}^{k_t'}\lambda_5(k)n]C_a \qquad (4)$$

There is a relationship described as Eqs. (5)-(7)

$$\sum_{k=k_t}^{k_t'}\lambda_1(k) + \sum_{k=k_t}^{k_t'}\lambda_2(k) = \frac{\pi_a}{\delta} \qquad (5)$$

$$\sum_{k=k_t}^{k_t'}\lambda_5(k)\delta = \lambda\pi_a \qquad (6)$$

$$\sum_{k=k_t}^{k_t'}\lambda_1(k) = \eta\sum_{k=k_t}^{k_t'}\lambda_2(k) \qquad (7)$$

Considering Eqs. (4)-(7), Eq. (4) can be equivalently rewritten as

$$\sum_{k=k_t}^{k_t'}[u_a'(k) - z_a'(k)] = [\frac{\eta\omega_{i1} + \omega_{i2}}{(\eta+1)} - \lambda n] \times \pi_a C_a/\delta = \Delta_a\pi_a/\delta \qquad (8)$$

Δ_a is called a bottleneck indicator to estimate the general bottleneck degree of individual road during the period of δ in urban transportation networks. Similarly, for the signal timing plan Y4Ÿ2, the relationship can be described as

$$\sum_{k=k_t}^{k_t'}[u_a'(k) - z_a'(k)] = [\frac{\eta\omega_{i1} + \omega_{i2}}{\gamma(\eta+1)} - \lambda n] \times \pi_a C_a/\delta = \Delta_a\pi_a/\delta \qquad (9)$$

(2) Y and Ÿ: four-phase controls (signal timing plan Y4Ÿ4)

Equation (10) can be obtained similarly.

$$\sum_{k=k_t}^{k_t'}[u_a'(k) - z_a'(k)] = [\frac{\eta\omega_{i1} + \omega_{i2}}{\gamma(\eta+1)} - \frac{\varphi\omega_{j1} + \omega_{j2}}{\mu(\varphi+1)}]\pi_a C_a/\delta = \Delta_a\pi_a/\delta \qquad (10)$$

For the signal timing plan Y2Ÿ4, it is described as

$$\sum_{k=k_t}^{k_t'}[u_a'(k) - z_a'(k)] = [\frac{\eta\omega_{i1} + \omega_{i2}}{\eta+1} - \frac{\varphi\omega_{j1} + \omega_{j2}}{\mu(\varphi+1)}]\pi_a C_a/\delta = \Delta_a\pi_a/\delta \qquad (11)$$

From the equations above we can find

(1) When a two-phase signal control is chosen at intersection Y, $X_a^{\pi_a}$, which is the maximum number of vehicles entering road α during the total effective green time π_a, can be computed as

$$X_a^{\pi_a} = \frac{(\eta\omega_{i1} + \omega_{i2})\pi_a C_a}{(\eta+1)\delta} \qquad (12)$$

(2) When a four-phase signal control is chosen at intersection Y, $X_a^{\pi_a}$ can be computed as

$$X_a^{\pi_a} = \frac{(\eta\omega_{i1} + \omega_{i2})\pi_a C_a}{\gamma(\eta+1)\delta} \qquad (13)$$

(3) When a two-phase signal control is chosen at intersection Ÿ, $\theta_a^{\pi_a}$, which is the maximum number of vehicles leaving road α during total effective green time π_a, can be computed as

$$\theta_a^{\pi_a} = \frac{\lambda n\pi_a C_a}{\delta} \qquad (14)$$

(4) When a four-phase signal control is chosen at intersection Ÿ, $\theta_a^{\pi_a}$ can be computed as

$$\theta_a^{\pi_a} = \frac{(\varphi\omega_{j1} + \omega_{j2})\pi_a C_a}{\mu(\varphi + 1)\delta} \qquad (15)$$

3 Identification approaches

3.1 Identifying a bottleneck road

Traffic bottleneck of road α is determined by bottleneck indicator Δ_a. It is related to signal timing parameters, i. e. , η, φ, $1/\gamma$, $1/\mu$, λ, the numbers of left-turn lanes and straight-through lanes of upstream roads of road α, i. e. , ω_{i1}, ω_{i2}, and the numbers of left-turn lanes and straight-through lanes of road α, i. e. , ω_{j1}, ω_{j2}, and n.

Under the condition $\Delta_a > 0$, $X_a^{\pi_a} > \theta_a^{\pi_a}$, road α is a traffic bottleneck. In this case, $\theta_a^{\pi_a}$ is the bottleneck capacity. Once the entry traffic volume is larger than the value of $\theta_a^{\pi_a}$, traffic bottleneck is active and road α will accumulate vehicles in signal scheduling. The higher the value of Δ_a, the higher probability traffic congestion.

Under the condition $\Delta_a = 0$, $X_a^{\pi_a} = \theta_a^{\pi_a}$, road α is in a critical state.

Under the condition $\Delta_a < 0$, $X_a^{\pi_a} < \theta_a^{\pi_a}$, road α is a bottleneck-free road. In this case, road α can dissipate congested vehicles in the signal scheduling.

3.2 Identifying a bottleneck-prone road

Although the above criterion can identify traffic bottleneck roads, it is necessary to find out a practical approach to quickly identify bottleneck-prone roads in transportation networks too.

Consider Eqs. (12) and (15), let $\omega_{i1} = \omega_{j1}$ and $\omega_{i2} = \omega_{j2}$, we can get $X_a^{\pi_a} \in [\min(\omega_{i1}, \omega_{i2}), \max(\omega_{i1}, \omega_{i2})]TC_a/\delta$ and $\theta_\mathrm{a}^{\pi_a} \in 1/\mu[\min(\omega_{i1}, \omega_{i2}), \max(\omega_{i1}, \omega_{i2})]TC_a/\delta$. Hence, the following empirical results are observed: the roads configured with signal timing plan Y2Ÿ4 are bottleneck-prone roads, while the roads configured with signal timing plan Y4Ÿ2 are possible bottleneck-free roads. In a word, a road, on which the number of phases at upstream intersections is lower than that at downstream intersections, is a bottleneck-prone road.

4 Optimization approaches

4.1 Optimization approaches for a traffic bottleneck road

Once a traffic bottleneck is identified, there are two optimization approaches.

Optimization approach (1): adjusting the values of signal timing parameters (i. e. , η, φ, $1/\gamma$, $1/\mu$, λ) to make the condition to $\Delta_a < 0$ and turning a bottleneck road into a bottleneck-free road. In this way traffic congestion would dissipate and the activations of the traffic bottlenecks would be eliminated.

For a bottleneck road, bottleneck capacity $\theta_a^{\pi_a}$ is virtually determined by the signal timing parameters of downstream intersections, i. e. , φ, $1/\mu$, λ. So the following optimization approach is induced.

Optimization approach (2): adjusting the values of signal timing parameters, φ, $1/\mu$, λ, to increase the value of $\theta_a^{\pi_a}$. Even if the condition $\Delta_a > 0$ still exist, this approach would improve the bottleneck capacities.

4.2 Optimization approach for a regional network

For practical purposes, it is impossible to adjust signal timing for a single traffic bottleneck. Adjustment of signal timing at an intersection has to consider its action for all the adjacent roads and other intersections. There are five vectors related with signal timing adjustment.

(1) $\Delta = (\Delta_1, \cdots, \Delta_m)$, $\Delta_m = G(\eta_{s1}, \varphi_{s2}, 1/\gamma_{s1}, 1/\mu_{s2}, \lambda_{s2})$. Function G is shown as Eqs. (8)-(11).

(2) $\Delta' = (\Delta'_1, \cdots, \Delta'_m)$, Δ'_m is a desired vector corresponding to Δ_m.

(3) Vector of effective green time $T = (T_1, \cdots, T_s)$, T_s is the total initial effective green time of all phases of signalized intersection.

(4) Vector of phases $P = (P_1, \cdots, P_s)$, $P_s = (p_{s1}, p_{s2}, \cdots, p_{sv})$, $v \in \{2, 3, 4, 5\}$.

(5) Use effective green times of all intersections as decision variables, i. e. , a vector $\xi = (\xi_1 = (g_{11}, g_{12}, \cdots, g_{1v}), \cdots, \xi_s = (g_{s1}, g_{s2}, \cdots, g_{sv}))$ represents a signal timing plan for a regional network, g_{sv} is the length of effective green time of phase p_{sv}. g_{sv} should satisfy the following equations

$$\min(F(\xi)) = \sum_{t=1}^{m} (\Delta_t - \Delta_t')^2 \quad (16)$$

$$\text{s.t.} \sum_{t=1}^{v} g_{st} = T_s \quad (17)$$

where $F(\xi)$ is an objective function to reduce the risk of high variance of bottleneck indicator, which is not a convex function. Eq. (14) is a constraint condition, indicating the total length of effective green time of phases at an intersection keeps constant.

To search ξ, a heuristic algorithm is appropriate, especially ant colony algorithm (He and Hou 2012). The algorithm processes are depicted as follows.

Step 1: Initialization.

Step 1.1: Perform the transportation network loading, including intersections, roads (with properties of intersections linked, i. e., ω_{j1}, ω_{j2}, and n), and the phases setting (length of light time, type of phase, traffic flows controlled by this phase at intersections). Update ω_{i1} and ω_{i2} of road according to ω_{j1} and ω_{j2} of its upstream roads.

Step 1.2: Constant setting, such as ANTS(number of ants), TIMES(number of ants' moving times), PE (rate of pheromone evaporation), PST(probability of state transitions), S_RADIUS (radius of local search), L_RADIUS (radius of global search).

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

Step 2.1: Under the condition of Eq. (17), conduct a stochastic global search. $\xi = \xi^A + \xi^\Omega$, where ξ^A is a vector representing the initial length of effective green time; ξ^Ω is a vector with global stochastic radius of effective green time length.

Step 2.2: Compute $F_t(\xi)$ according to Eqs. (8)–(11), (16).

Step 3: Search optimal ξ.

Step 3.1: If traversal times are greater than TIMES, go to Step 4.

Step 3.2: Compute transition probabilities for each ant according to

$$\rho(t) = 1 - F_t(\xi)/\max(F_1(\xi), \cdots, F_t(\xi)) \quad (18)$$

Step 3.3: Under the condition of Eq. (17), if $\rho(t) > \text{PST}$, conduct a global search of effective green time length; otherwise, conduct a local search.

Step 3.4: Compute $F_t^A(\xi + \xi^\Omega)$ according to Eqs. (8)–(11), (16), if $F_t^A(\xi + \xi^\Omega) < F_t(\xi)$, let $\xi = \xi + \xi^\Omega$.

Step 3.5: Update the amount of pheromone according to

$$F_t(\xi) = (1 - PE) \times F_t(\xi) + 1/F_t^A(\xi) \quad (19)$$

Step 3.6: $t = t + 1$, if $t <$ ANTS, go to Step 3.2.

Step 3.7: Go to Step 3.1.

Step 4: Output ξ and Δ.

5 Case study

Figure 3 is a small experimental transportation network in CBD of Xi'an, Shaanxi Province with four intersections A, B, C, and D. Fig. 4 shows the phases setting at intersections A, B, C, and D.

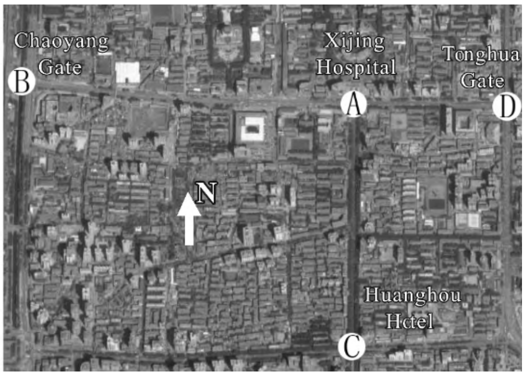

Fig. 3 An experimental transportation network

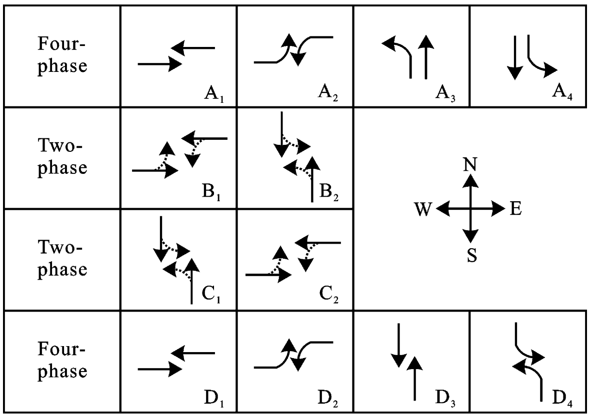

Fig. 4 Phase sequence at intersections A, B, C, and D

Phase A_1 is denoted by (71, 2, 120) which means the green time of 71 s, yellow time of 2 s, and the red time of 120 s. The others are: Phase A_2(21, 2, 170), Phase A_3(35, 2, 156), Phase A_4(41, 2, 150), Phase B_1(66, 2, 60), Phase B_2(54, 2, 72), Phase C_1(61, 2, 71), Phase C_2(65, 2, 67), Phase D_1(78, 2, 115), Phase D_2(46, 2, 147), Phase D_3(43, 2, 150), Phase D_4(13, 2, 180).

When $\delta = 30$ s and $C_a = 10$, in terms of Eqs. (8)–

(11), we can compute individual bottleneck indicator Δ_a at interval of δ, as shown in Tab. 4.

The values of Δ_a in Tab. 4 give an estimation of bottleneck degree of individual road in experimental transportation network universally. The results indicate that R_{CA}, R_{BA}, R_{AD} are traffic bottlenecks. Though R_{BA} is a bottleneck-prone road according to signal timing plan Y2Ÿ4, the value of Δ_a is not prominent due to $\omega_{j2} > \omega_{i2}$. Similarly, though R_{AD} is not bottleneck-prone road according to signal timing plan Y4Ÿ4, the value of Δ_a is relatively high due to $\omega_{j2} < \omega_{i2}$.

Tab. 4 Properties of roads in experimental network

R_m	Type	ω_{i1}	ω_{i2}	ω_{j1}	ω_{j2}	n	Δ_a
$R_1(R_{\mathrm{AB}})$	Y4Ÿ2	1	3	1	2	3	-2.67
$R_2(R_{\mathrm{BA}})$	Y2Ÿ4	1	2	1	3	4	2.46
$R_3(R_{\mathrm{AC}})$	Y4Ÿ2	1	2	1	2	2	-3.76
$R_4(R_{\mathrm{CA}})$	Y2Ÿ2	1	2	1	2	2	10.57
$R_5(R_{\mathrm{AD}})$	Y4Ÿ4	1	3	1	2	3	2.91
$R_6(R_{\mathrm{DA}})$	Y4Ÿ4	1	2	1	3	4	-3.57

Table 5 displays a snapshot of traffic conditions, free-moving and slow-moving, quoting from Baidu website. Like Google, Baidu provides the function of prediction of traffic conditions with its statistical traffic data. The predicted values vary slightly on different days of the week, so the status shown in Tab. 5 is called a snapshot. Prediction of traffic conditions with statistical data can shield off the stochastic influences, like traffic accidents, and reflect the certain regular influences, such as signal timing at intersections, properties of left-turn lanes and straight-through lanes of roads, and road maintenance, etc.

In a certain extent, traffic conditions are determined by the number of vehicles on roads, traffic condition has a certain relationship with traffic bottleneck. From Tab. 5, we can see:

(1) During the period of 7:00-9:00, 10:00-13:00, and 15:00-19:00, the overall networks have a status of slow-moving. Traffic congestion occurs everywhere. During the period of 22:00-5:00, the overall networks have a status of free-moving. At these times, no traffic bottlenecks appear in urban transportation network.

(2) The bottleneck effects occurring on R_{CA}, R_{AD}, which identify traffic bottlenecks, are obvious. They have a status of slow-moving for longest time. Besides, R_{CA} has a status of slow-moving while one of its downstream roads, R_{AB}, has a status of free-moving during the period of 19:00-21:00. R_{AD} has a status of slow-moving while one of its upstream roads, R_{BA}, has a status of free-moving during the period of 19:00-21:00.

(3) The effects of identified bottleneck-free roads R_{AC}, R_{AB} are obvious as well, because R_{AC} has a status of free-moving while others in the network have a status of slow-moving during the periods of 9:00-10:00 and 13:00-15:00. R_{AB} has a status of free-moving while its upstream roads and downstream roads have a status of slow-moving during the period of 19:00-21:00.

(4) The traffic conditions on R_{BA} and R_{DA} contradict the estimations of them. Though R_{BA} is identified as a traffic bottleneck, it appears to be a bottleneck-free road. During the period of 19:00-21:00, it has a status of free-moving while its downstream road R_{AD} has a status of slow-moving. The reason is that the right-turn and some straight-through vehicles can divert along the branch road. And for R_{DA}, though it is identified as a bottleneck-free road, it appears to be a traffic bottleneck. During the period of 19:00-21:00, R_{DA} has a status of slow-moving while its downstream road R_{AB} has a status of free-moving. The reason is that the vehicles queuing into Xijing Hospital often have negative effects on the traffic conditions of R_{DA}.

(5) Status transition from free-moving to slow-moving on the bottleneck-free roads indicates traffic congestion occurring in regional network. On the contrary, the status transition from slow-moving to free-moving on bottleneck-free roads indicates the dissipation of traffic congestion in regional network.

Through the above analysis, we can know that the status transitions occurring on identified bottlenecks, R_{CA} and R_{AD}, as well as the identified bottleneck-free roads, R_{AC} and R_{AB}, are in accordance with the estimations. As to R_{BA} and R_{DA}, the actual status transitions are contrary to the estimations, which indicate the model has some limitations, i. e., only considering the factors of signal timing at intersections, left-turn flows, and straight-through flows, whereas ignoring the factors of right-turn flows, diverting traffic flows through branch roads, road maintenance, etc. However, the contrary estimations can still help us to fix other virtual factors which have effects on the status transitions of traffic conditions, so it is meaningful at this respect as well.

Tab. 5 Snapshot of Baidu prediction for traffic conditions with its statistical traffic data

Time	R_{AB}	R_{BA}	R_{AC}	R_{CA}	R_{AD}	R_{DA}
5:00	○	○	○	○	○	○
6:00	●	●	○	●	●	●
7:00	●	●	●	●	●	●
8:00	●	●	●	●	●	●
9:00	●	●	○	●	●	●
10:00	●	●	●	●	●	●
11:00	●	●	●	●	●	●
12:00	●	●	●	●	●	●
13:00	●	●	○	●	●	●
14:00	●	●	○	●	●	●
15:00	●	●	●	●	●	●
16:00	●	●	●	●	●	●
17:00	●	●	●	●	●	●
18:00	●	●	●	●	●	●
19:00	○	○	●	●	●	●
20:00	○	○	○	●	●	●
21:00	●	○	●	●	●	○
22:00	○	○	○	○	○	○
23:00	○	○	○	○	○	○

Note: ○ free-moving; ● slow-moving.

The large variance of roads Δ_a in the experimental network indicates that optimization strategies should apply. The related parameters are: ANTS = 200; TIMES = 100; PE = 0.8; PST = 0.2; S_RADIUS = 2; L_RADIUS = 10; $T = (176, 124, 130, 188)$.

Strategy 1: Only optimization of signal timing applied at intersection A.

Let $\Delta' = (0, 0, 0, 0, 0, 0)$, $\xi^A = ((73, 23, 37, 43))$, one pair of the optimization results are $\xi = ((61, 19, 49, 47))$, $\Delta = (-3.92, 4.53, -3.54, 9.33, 1.25, -1.49)$.

Strategy 2: Optimization of signal timing applied at all the intersections in experimental network.

Let $\Delta' = (0, 0, 0, 0, 0, 0)$, $\xi^A = ((73, 23, 37, 43), (68, 56), (63, 67), (80, 48, 45, 15))$, one pair of optimization results are $\xi = ((51, 61, 59, 5), (43, 81), (18, 112), (83, 21, 42, 42))$, $\Delta = (0.91, 1.96, 0.99, 4.93, -1.40, -0.42)$. Although the optimization results seem good, there is a preference in optimization that only roads in experimental network are considered, other roads, which are out of experimental network but adjacent to intersections B, C, and D, are not considered.

Strategy 3: Optimization of the signal timing with desired values applied at all the intersections in the experimental network.

To correct above deviations, the desired vector, $\Delta' = (-3, 3, -3, 7, 3, -3)$, is given. One pair of the optimization results are $\xi = ((55, 46, 55, 20), (58, 66), (43, 87), (52, 15, 73, 48))$, $\Delta = (-2.2, 3.29, -1.96, 7.21, 3.48, -3.14)$. Compared with Strategies 1 and 2, the optimized signal timing plan obtained in Strategy 3 is relatively reasonable and practical, and reflects the integrated result of coordination of signal timing at intersections. When traffic bottlenecks or bottleneck-free roads appear in urban transportation network, Strategy 3 can be applied to mitigating traffic congestion by reducing the risk of high variance of bottleneck indicator.

6 Conclusions

This paper quantitatively investigated the relationship between traffic bottleneck roads and the related intersection signal timings. Firstly, under a certain kind of phases at upstream or downstream intersections of roads, the entry or exit saturation flow volumes were depicted by the signal timing and entry or exit lane parameters. Then, a new bottleneck indictor was introduced to represent the comprehensive bottleneck degree of individual road in regional networks. As a result, the nature of accumulation or dissipation of vehicles on roads could be determined, and thus traffic bottlenecks could be identified. Similarly, it was found that bottleneck-prone roads were generated merely by kinds of phases at their upstream and downstream intersections. Now that a bottleneck indictor of a road is related to the signal timing of signalized intersections at ends of the road, adjusting signal timing at an intersection will have effects on all the bottleneck indictors of adjacent roads. With adopting ant colony algorithm seeking for the optimal signal timing plan for a regional network, an optimization method was proposed, with aim to mitigate the bottleneck degree through reducing the risk of high variance in bottleneck indicators.

In general, the introduced bottleneck indicator affected by the signal timing could play a critical role in identifying and optimizing traffic bottlenecks, which has been proved by its application experimentally analyzing real cases in a city traffic network.

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