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过饱和状态交通信号控制方法综述

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摘　要:为向拥堵状态城市路网的交通控制优化提供依据,综述并评价了过饱和状态的交通信号控制策略;分析了过饱和状态交通流的特征,提出了过饱和状态交通信号控制的对应优化原理;从单点交叉口、协同控制交叉口及路网 3 个层次对过饱和状态交通控制方法进行了总结与评价,应用 VISSIM 仿真环境评价了已有控制策略的适用性;总结了具备处理过饱和状态能力的自适应交通信号控制系统的控制策略。仿真结果表明:过饱和状态的交通信号控制应优先优化道路空间的分配矛盾;排队管理策略对过饱和交通流具有较好的优化效果;建议在进行过饱和交通信号控制优化时,结合实时交通信息,采用排队管理、关键路径通行能力最大等控制策略,在交叉口群或路网层面对交通信号控制方案进行优化。

关键词:交通信号控制;过饱和状态;控制策略;排队管理;交通仿真

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Review of traffic signal control methods under over-saturated conditions

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Abstract: To provide references for traffic control optimization at congested urban road network, various traffic signal control strategies under over-saturated conditions were reviewed and evaluated. Based on the analysis of the characteristics of over-saturated traffic flow, the corresponding optimization principles of traffic signal control under over-saturated conditions were proposed. The traffic control strategies for isolated intersection, coordinated intersections and road network were summarized and evaluated by using VISSIM simulation environment. The control measures of adaptive traffic signal control system with the capability to deal with over-saturated conditions were summarized. Simulation result indicates that traffic signal control strategies under over-saturated conditions should optimize the allocation of road space in the first place. The queue management strategy has better performance on optimizing traffic signal under over-saturated conditions. It is suggested that the strategies like queue ratio maintenance and throughput maximization for critical route should be utilized with real-time traffic information for the optimization at the intersection group or road network level. 4 tabs, 7 figs, 56 refs.

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Key words: traffic signal control; over-saturated condition; control strategy; queue management; traffic simulation

0 Introduction

Traffic signal control plays an evidently important role in urban transportation system management. However, the commonly used traffic control method, such as TRRL (transport and road research laboratory) method[1], HCM (highway capacity manual) method[2] or adaptive traffic control software like SCATS (Sydney coordinated adaptive traffic system)[3] and SCOOT (split cycle offset optimizing technique)[4], can not work efficiently enough when the traffic demand approaches or exceeds the capacity[5]. The major reason that these mature traffic control strategies have low efficiency under over-saturated conditions is that they can not respond to the primary restrictions of over-saturated traffic system, which changes from the allocation of passing time to the spatial space limitation along road section[6]. Thus, specific signal control strategies are needed for over-saturated traffic system[7]. During the past 50 years, many traffic control strategies were designed for over-saturated traffic system. The purpose of this paper is to summary and evaluate the existing traffic control strategies for over-saturated conditions, and provides a reference way to optimize traffic signal control for congested urban road network.

Traffic control strategies under over-saturated conditions are firstly implemented for isolated intersections. Specific coordinated traffic signal control strategies for the arterial and road network are then developed for the purpose of dealing with congestion status. Beginning with distinguishing the conceptions of approaching saturation, saturation and over-saturation, the over-saturated traffic control strategies for various scales are summarized and evaluated. As a part of the advanced traffic management system (ATMS)[8], adaptive traffic signal control systems with the capabilities of handling over-saturated flow are also discussed.

1 Definition and characteristics of over-saturation

Traffic status is generally determined by traffic intensity, i. e. V/C (volume/capacity) ratio. For a road section, approaching saturation usually refers to the situation of V/C ratio larger than 0.9[9], and over-saturation is the traffic status with V/C ratio greater than 1.0, the saturation status has a V/C ratio exactly equals 1.0. The conceptions of traffic conditions at intersection are similar to the conceptions at road section. If the traffic demand of one approach of the intersection exceeds its capacity, this intersection is under over-saturated status. As shown in Fig. 1, because it is difficult to measure the actual traffic demand and capacity when the traffic system is congested, the over-saturation at signalized intersection can be defined as the condition of having an approach with residual queue[6]. The queue information can be directly estimated by loop detectors[10], mobile sensors[11] or video[12] data by using shockwave theory.

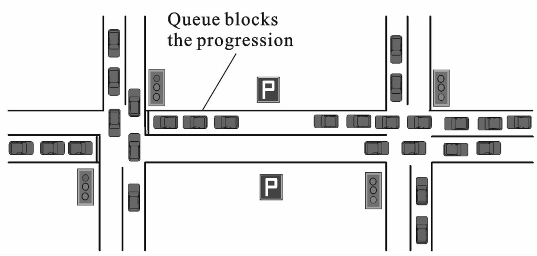

Fig. 1 Residual queues at intersections

Traffic flow will become unstable under over-saturation or approaching saturation conditions. A small fluctuation from any vehicle in a platoon may cause adverse consequences and reduce the efficiency of traffic system sharply. The low stability of saturated traffic flow puts forward more stringent requirements to the traffic control system.

Generally, over-saturated condition will firstly appear at one or several isolated intersections with relatively high saturation degrees. As shown in

Fig. 2, when intersection B can't discharge the queue, it turns into over-saturated status. The queue will continually grow until it exceeds the road section between intersections A and B. At the moment the residual queue reach intersection A, both intersections are under the over-saturated conditions. No effective traffic control strategy exists at this moment, but to prevent any vehicle from entering over-saturated road section. This detrimental effect is named spillback, which should be avoided in the first place. Intersections along the route with larger traffic volumes may spread the congestion much faster than other routes. Finally, the whole road network will be congested, even under a lock-out status[13]. It is important to implement traffic signal control strategies to prevent over-saturated conditions in the first place, rather than to react to the issues after the fact. Once the traffic demand goes back to the normal level, the frequently used traffic control strategy will make the practitioners manage the traffic flow easily. The cause of over-saturated status indicates that the decline of capacity caused by detrimental effects is a critical interfering factor. Therefore, the essence of traffic control strategies under over-saturated status is to eliminate the detrimental effects by adjusting green time, cycle length and offset.

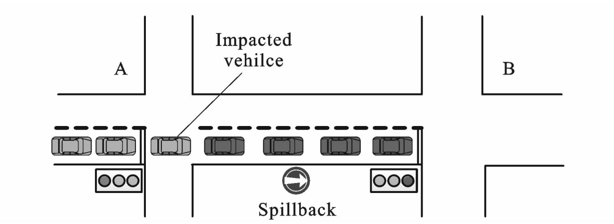

Fig. 2 Spillback at intersections

2 Over-saturated control strategies for isolated intersection

2.1 Existing traffic signal control strategy

2.1.1 Optimization of fixed timing

Since Webster connected the average delay with the signal timing parameters and the observed variables by using cumulative diagram, these parameters can be optimized by minimizing the delay of signalized intersection (knowing as TRRL method)[1]. Similar to TRRL method, many optimization objectives are also applied in signal timing optimization process, such as minimizing cycle failures[14], minimizing stops[15] and minimizing average saturation degree[2]. However, because of the principle of algorithm, they can hardly be utilized under over-saturated conditions. Although the coordinate transformation model[16-17] and the deterministic model[18] were established to estimate the delay or queue in the signalized intersection with relatively high saturation degree, the traffic signal control can do nothing but to allocate more green time to reduce the delay.

2.1.2 Switching of green

When the green time becomes flexible, switching of green is the first and simplest traffic control strategy for the over-saturated intersections. This strategy can allocate the unused green time from un-congested phase to over-saturated phase to ensure the elimination of residual queue. By applying this control philosophy, the total delays can be minimized by maximizing intersection productivity, while keeping the queues' development within acceptable levels at the same time. A maximum green time is given to the movement with the higher saturation flow until the queue is dissipated, while other movements receive the minimum green time[19].

Widely used technologies of this strategy include semi/full actuated control, NEMA's (national electrical manufactures association) ring-barrier phase model in North America, and phase stage model[20-23] in Europe. In the actuated control system, controller can extend or terminate the current phase to allocate the unused green to congested phase. NEMA's ring-barrier phase model extends the idea of actuated control. As illustrated in Fig. 3, the dual ring control unit can give more priority (i. e. more green time) to traffic flow of specific intersection approach by adjusting the barriers between phases 1, 5 (3, 7) and 2, 6 (4, 8). Phase stage model can group all the un-conflicted movements and order them by priorities. The phase associated with critical movement group can get more green time.

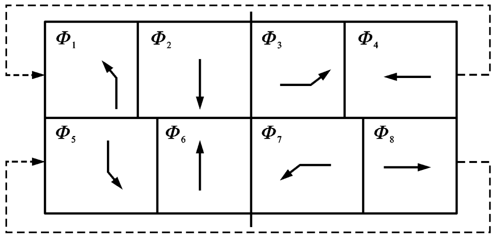

Fig. 3 Typical dual ring control unit of NEMA

The switching of green strategy does improve the efficiency of traffic signal system, especially for the situation of intersection with only one or two movements being congested. However, when the volumes of all movements exceed their capacity, these algorithms will extend all phases to maximum green time. At that time, traffic control system has no differences with fixed time control. In general, minimizing delay via split switching is not an on-line highly responsive policy, but an optimization policy based on advanced mathematics and the detailed knowledge of demand[24].

2.1.3 Maintaining queue ratio

The nature of green adjustment police is to re-allocate the temporal resources for the purpose of improving their efficiencies. However, when the road space becomes the restriction of the system, maintaining queue ratio should be selected as the optimization object[25]. Under this strategy, the green time should be adjusted to balance the queues at intersection's approaches. The objective is to minimize the number of blocked intersections by managing queues of critical intersection[26]. This strategy involves the use of sampled loop data at each intersection[10, 27] or mobile sensors data[11]. Recent studies indicated that the signalized intersection won't maximize its capacity and minimize its delay at the same time under approaching saturated or over-saturated conditions[28]. In this way, signal optimization objectives should be switched to the measures of reducing the queue length at the bottleneck and minimizing the detrimental effects under over-saturated status. These optimization objectives involve the throughput maximization or the queue minimization of critical route.

2.2 Simulation based evaluation

2.2.1 Simulation environment

In order to evaluate the performance of traffic control strategies for over-saturated isolated intersection, fixed timing method (TRRL method), Synchro method (HCM method), actuated control method, NEMA's dual ring control unit, phase stage model and queue ratio maintenance method are evaluated in the prevailing microscopic traffic simulation environment based on VISSIM simulation system. The advantages of VISSIM over other simulation packages include some aspects as follows.

(1) VISSIM provides the largest flexibility for users to calibrate driving behaviors and traffic conditions.

(2) VISSIM is developed under .NET framework, which brings flexibility for add-on program development.

(3) VISSIM provides the best tools for the development of signal control strategies, such as NEMA controller emulator, vehicle actuated programming (VAP) language, signal control application programming interfaces (SCAPIs), etc.

VISSIM SCAPI method is used to develop signal control emulator in this research. SCAPIs are written in C++/CLR language and the original version of SCAPIs controller requires signal control algorithms be embedded into a single dynamic link library (DLL) file. To facilitate the development, a middleware is developed, which can synchronously collect all the real-time detectors/phases states from the VISSIM network to the controller emulator then return the new desired phase states back to the VISSIM network[29]. At each time step, controller runs the algorithm, makes decisions according to the current state, then returns the new desired phase states to the VISSIM network. The concept of this simulation environment is illustrated as in Fig. 4.

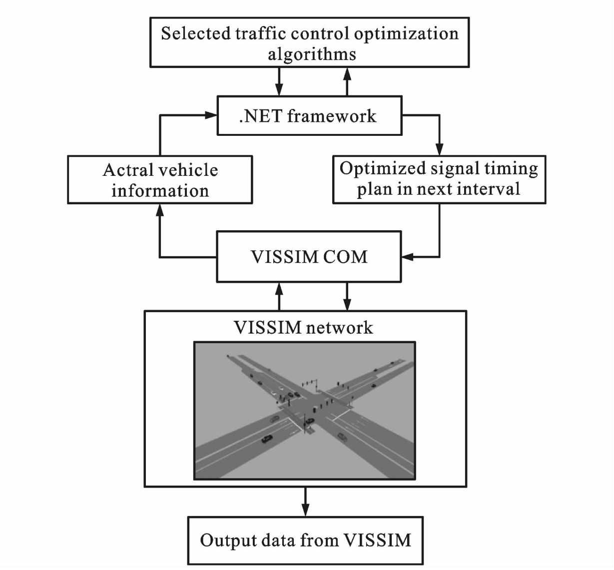

Fig. 4 Simulation environment of VISSIM

2.2.2 Experimental design

A simple four way intersection is selected to evaluate the selected algorithms. The geometric characteristics of the intersection are shown in Fig. 5. The experimental configurations are listed in Tab. 1. All the needed data can be directly obtained from the VISSIM software. All the input parameters are optimized in advance, and then are input to the VISSIM environment. The VISSIM software has a built-in fixed time controller to achieve TRRL method and HCM method. The Crossing software and VisVAP module in VISSIM are applied to program the actuated control method, phase stage model and queue ratio maintenance method. The VISSIM standard NEMA editor is utilized to evaluate the dual ring control unit.

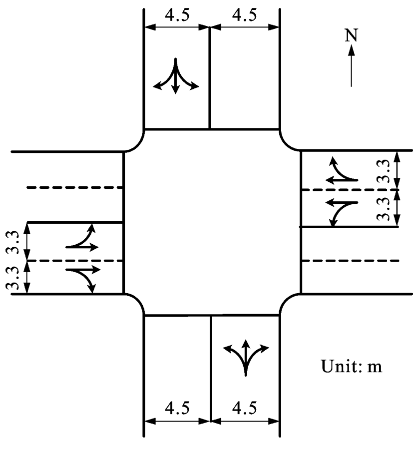

Fig. 5 Intersection geometry

Tab. 1 Experimental traffic volumes pcu • h^{-1}

Movement	Eastbound		Westbound		Northbound		Southbound	
	Low	High	Low	High	Low	High	Low	High
Left turn	65	90	30	45	30	45	10	60
Throughput	620	880	700	990	370	530	510	720
Right turn	35	50	20	45	20	25	50	70

2.2.3 Result analysis

Each scenario runs for 50 times to conduct statistical analysis. Throughput vehicles and average queue ratio are selected to compare the selected traffic control methods. As shown in Tab. 2, it can be indicated that under normal conditions, the actuated control method, the NEMA method and the phase stage method all have similar performances. The flexible green control strategies, such as actuated control, NEMA and phase stage, have relatively better performance than the fixed timing control strategies (TRRL, HCM). Although the queue ratio maintenance method has good performance in managing the queue ratio, this control strategy is not the most efficient one under normal conditions. However, under over-saturated conditions, the queue ratio maintenance method has better performance than all other strategies, and thus, it is suitable to be utilized under congested conditions. If the traffic demand continues to grow, specific traffic control strategies for larger range are needed to be concerned.

Tab. 2 Comparison of evaluation results

Algorithms	Throughput vehicles/pcu		Average queue ratio	
	Normal	Over-saturated	Normal	Over-saturated
TRRL	2 294	2 986	0.46	>1.00
HCM	2 298	3 018	0.44	>1.00
Actuated control	2 325	2 996	0.45	>1.00
NEMA	2 322	3 041	0.43	>1.00
Phase stage method	2 318	3 008	0.44	>1.00
Queue ratio maintenance	2 309	3 328	0.41	0.99

3 Strategies for coordinated intersections

3.1 Existing coordinated traffic control strategies

3.1.1 Optimization of progression band

Signal coordinated control strategies try to seek for the maximum progression band by adjusting the offsets between green phases under steady traffic conditions. With predefined maximum likelihood offsets, coordinated timing plans are generally designed for traffic flow under steady states. As the intersections become more saturated, residual queues start to disrupt movement at upstream intersections. Then, the progression band is not applicable any longer[30]. If the over-saturated condition lasts for a considerable time period, fixed-timing signal coordination is likely to aggravate movement disturbance, which may cause spillback[31] into upstream intersections[32].

Variable-bandwidth progression[33-34] is then established to adjust the offsets according to the travel time information in real time. As shown in Fig. 6, the variable-bandwidth progression improves the efficiency of coordinated control, and makes it work at most conditions. The Monte Carlo method[35] can be utilized to optimize the bandwidth to prevent the early started coordinated green phase in the actuated signal system. Under over-saturated conditions, the real-time information is hard to obtain. Meantime, in order to make more vehicles pass through the progression band, the bandwidths tend to be large, which makes signal timing to be fixed (maximum green at the critical route and minimum green at other route)[36].

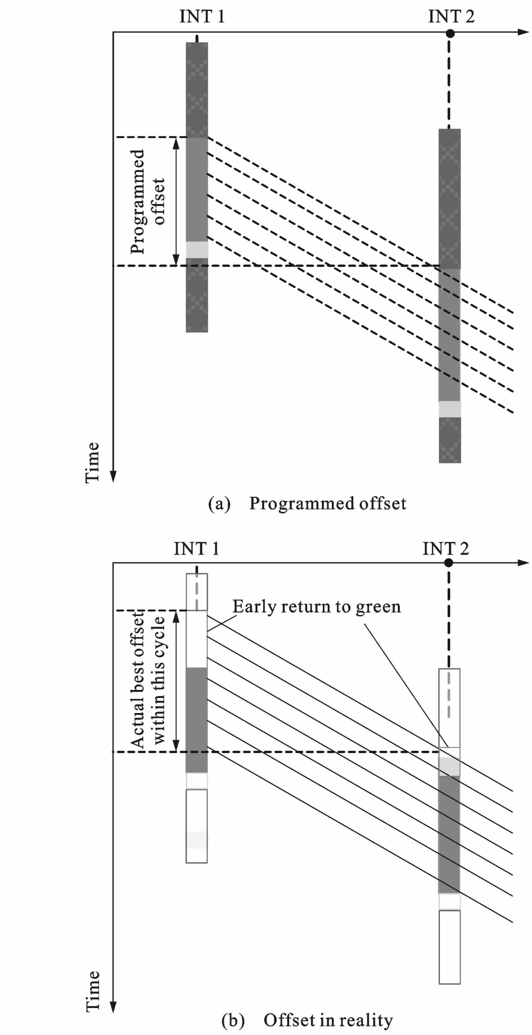

Fig. 6 Dynamic offsets in actuated coordination

3.1.2 Maximum storage capacity

Instead of searching the maximum progression band, the strategy of maximum storage capacities of approaches is utilized to optimize queues at intersection approaches[37]. This method responds to the restrictions of road space under the over-saturated conditions, and tries to make efficient use of upstream link's storage capacity. The procedure of using simultaneous offsets along the arterial and negative offsets with flaring of green along cross roads is then tested under the over-saturated arterial network. Because of markedly decreased spillback blockages, the procedure of offset setting has larger throughput vehicle number than traditional offset setting, and with a 20% reduction in overall travel time[38]. With the possibility of high-resolution traffic data, recent researches described simple controller logic for truncating a phase early when faced to a downstream restriction of flow[39-40] and to avoid detrimental effect like "spillback" or "de-facto red"[13]. De-facto red assumes that no flow on a detector when the light is green indicating that there is nowhere for the vehicle to go, and thus it is better for overall intersection operations to move on to another phase[41].

3.2 Simulation evaluation

3.2.1 Evaluation setup

An arterial is selected to evaluate the performance of maximum progression band strategy, variable-bandwidth progression strategy, and maximum storage capacities strategy. The arterial is about 8.85 km long, four ways for two directions, and six signalized intersections. Fig. 7 shows its layout and traffic movement counts. The filed observed traffic is congested or close to congested. All six signalized intersections are controlled by the Econolite ASC/3 signal controllers and inductive loop detectors with four-way pedestrian phases.

The VISSIM SCAPI method is also utilized to evaluate the coordinated traffic control strategies. The original traffic signal timing plan is generated by Synchro, a prevailing signal timing optimization package in North America, using maximum progression band strategy. Fig. 7 also shows the optimized fixed timing plans of the selected intersections. The variable-bandwidth progression strategy and maximum storage capacities strategy are implemented by Crossing software and VisVAP module.

3.2.2 Result analysis

During the process of evaluation, each scenario runs for 50 times and summarizes the average value. Whenever the timing plans are updated and a platoon is identified, only phase splits are adjusted whereas the cycle lengths and offsets are kept unchanged. Therefore the coordination will not be destroyed on the mainline. Since the expected advantages of the maximum storage capacities strategy include providing signal timings to avoid queue spillback and queue clearance without destroying coordination. The following MOEs (measures of effectiveness) are chosen to evaluate the performance of the ACS control strategy: link travel time, total stops, the average control delay, and the maximum queue ratio on the mainline. Tab. 3 summarizes the MOEs for all the three traffic control strategies.

Tab. 3 MOEs comparison

Performance	Maximum progression band	Variable-bandwidth progression	Maximum storage capacities
South bound link travel time/s	1 156	1 278	1 029
North bound link travel time/s	1 043	1 032	970
South bound total stop/veh	6 765	7 254	5 683
North bound total stop/veh	4 064	4 147	3 576
Average control delay/s	30	33	29
South bound maximum queue ratio	>1.00	>1.00	0.97
North bound maximum queue ratio	0.91	0.90	0.87

From Tab. 3, it is clear that the maximum storage capacity strategy can reduce the link travel time and vehicle stop on the mainline by from 5% to 15%. However, the variable-bandwidth progression strategy has issues on optimizing the signal of south bound traffic, and cause serious

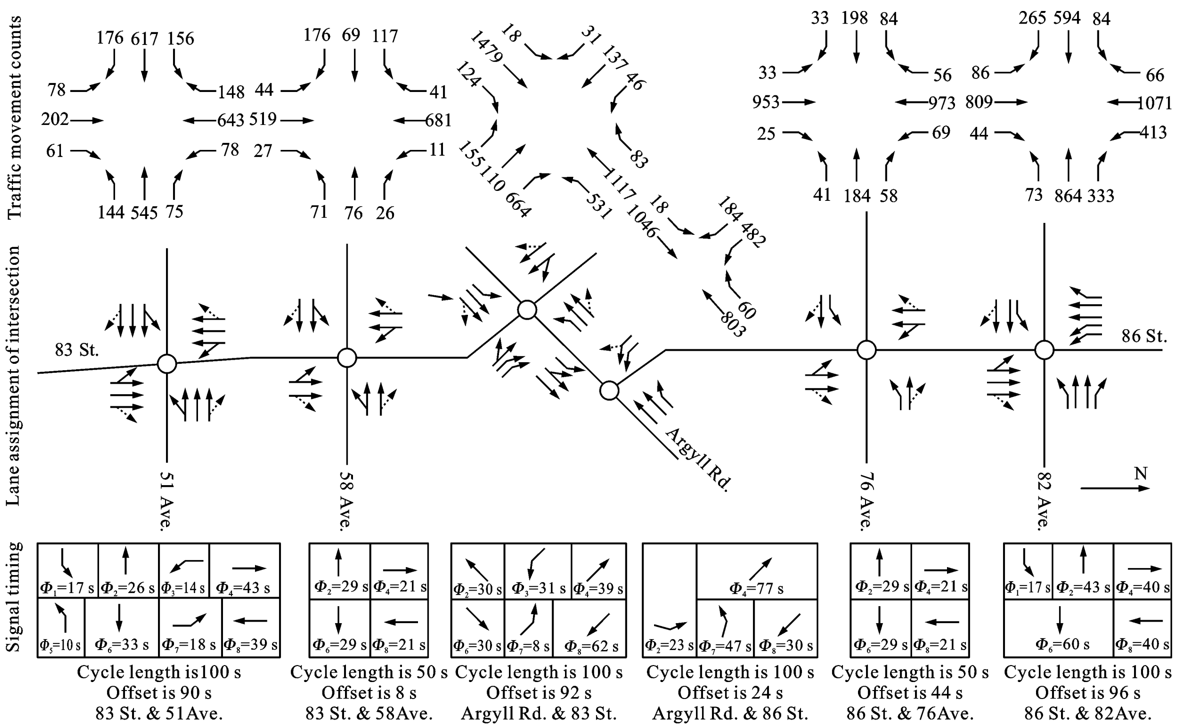

Fig. 7 Selected road network

congestion during simulation. Although the performance of north bound is slightly better than the fixed time scenario, the variable-bandwidth progression strategy is not suggested to be utilized under over-saturated conditions. The maximum storage capacity strategy does not significantly reduce the maximum queue ratio or control delays at intersections, because the distances between intersections are relatively long and the constraints regarding the relationship of the estimated maximum queue length and link length barely play a role during the optimization. It is expected that more benefit of queue spillback avoidance will be acquired if maximum storage capacity strategy is deployed at closely-spaced intersections.

4 Strategies for road network

The signal control strategies in the road network level are the extension of the strategies for coordinated intersections. Similar to the strategies for coordinated intersections, the strategies for road network can be divided into adaptive signal control and metering/gating police. The adaptive control strategies try to seek for a relatively better allocation of the passage time at the network level by applying hill climbing method or other heuristic algorithms. When the road space becomes a limitation for traffic signal optimization, it is suggested to distribute the traffic demand over the network, and make full use of the entire road space within the selected area. The metering police extends the queue management strategy. This strategy impedes traffic input at a suitable point or points upstream to prevent the demand from reaching critical levels at critical downstream locations[42]. It can manage the rate of flow into and within high-traffic density network[43]. One well-known real-time traffic control policy for congested arterials is RT/IMPOST (real-time/internal metering policy to optimize signal timing), which is designed to control queue development on every saturated approach by suitable metering traffic to maintain stable queues[44]. A traffic control strategy for intersection group under over-saturated condition further developed the RT/IMPOST strategy by adding critical route layer[5]. This procedure ensures the critical route[45-46] is the primary optimization object for over-saturated intersection group. In order to accomplish the road network control strategies, a number of models were developed to identify the queue, queue discharge time, available downstream storage, etc[47-49].

5 Adaptive traffic signal control system for over-saturated conditions

For the reason that the optimization objects under over-saturated conditions are different from the ones at steady states, specify modules or functions are needed to built in the traffic signal control system to deal with the over-saturated conditions. Generally, an adaptive traffic signal control system with the capability of working under over-saturated conditions should contain traffic status identification module, congestion cause identification module and several signal control parameters' optimization algorithms. Commonly used commercial adaptive traffic control systems generally have the capability of calculating saturation degree in approximately real time, such as the saturation percentage in SCOOT[4], or the degree of saturation in SCATS[3]. However, because of the reason that no specify algorithm is designed for over-saturated conditions, when the saturated degree approaches 1, the stability of these systems drops sharply[50]. To deal with the traffic congestion management problem, some adaptive traffic control systems are designed to avoid congestion or over-saturated conditions[51], such as SCOOT MC3[52], MOVA[53-54], TUC[55], and MOTION[56]. Detail measures applied in these systems are summarized in Tab. 4.

6 Summary of literature review

According to the optimization principles, the traffic signal control strategies can be divided into two categories: the allocation of temporal or spatial resources. Under steady states, the efficiency

Tab. 4 Characteristics of traffic control systems for dealing with over-saturated conditions

Adaptive traffic control systems	Optimization objects	Control strategies
SCOOT MC3 (Spilt Cycle Offset Optimization Technique, Managing Congestion, Communications and Control)	Road network	1. Traffic status identification and congestion cause identification 2. Congestion importance factor consideration 3. Traffic guidance of traffic demand from the overloaded junction to others
MOVA (Microprocessor Optimized Vehicle Actuation)	Isolated intersection extended for SCOOT in latest version	1. Traffic status identification 2. Specify optimization objective for over-saturated condition
TUC (Traffic-responsive Urban Control)	Road network	1. Two-levels structure 2. Metering/gating police 3. Specify optimization algorithm for cycle length, split and offset under over-saturated condition
MOTION (Method for the Optimization of Traffic Signals in Online Controlled Networks)	Road network	1. Traffic status identification 2. Metering/gating police 3. Specify optimization objective for over-saturated condition 4. Higher priority for critical route

can be improved by assigning more unused green to the movement with relatively higher saturation degree. However, under over-saturated conditions, the road space becomes a restriction that must be considered. If too much green time is assigned to one specify movement, the downstream road or other intersections will exceed their capacities, which may lead to the lock-out status. Hence, traffic control strategies under over-saturated conditions must consider the restriction of road space. Suggested control strategies at different levels are listed as below: maintaining queue ratio at isolated intersection level, the maximum storage capacities of approaches at the coordinated intersection level, and metering police at road network level. These measures are suggested to be utilized at the critical route at the network or critical intersections, which can be identified by high resolution traffic data.

Traffic signal control strategies for handling over-saturated conditions still have issues for improvements, which are listed as below.

(1) Real-time information is strictly needed to achieve the proposed traffic control strategies, particularly at the road network level. The implement of the proposed traffic control strategies, such as metering or adaptive traffic control, need traffic information, like queue length or critical route, to be updated at least every five minutes. Further development of traffic information acquisition method, like fusing the fixed location data and mobile sensor data, should be processed to support the proposed integration.

(2) The detrimental effects caused by over-saturation may spread to the whole road network in a very short time. Traffic signal control strategies should optimize the traffic flow along the route with critical conflicts in the first place. In this way, traffic control strategies should concern on intersections with strong traffic relevance, which can be named as intersection group.

(3) Traffic flow in China is different from other countries. Traffic signal parameters, such as green flashing, all red, should also be calibrated with local filed data before applying the selected strategies. Specific traffic signal control strategies particularly for Chinese urban road networks should also be considered to study.

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