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NSGA-Ⅱ based traffic signal control optimization algorithm for over-saturated intersection group

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Abstract: In order to improve the efficiency of traffic signal control for an over-saturated intersection group, a non-dominated sorting genetic algorithm Ⅱ (NSGA-Ⅱ) based traffic signal control optimization algorithm is proposed. The throughput maximum and average queue ratio minimum for the critical route of the intersection group are selected as the optimization objectives of the traffic signal control for the over-saturated condition. The consequences of the efficiency between traffic signal timing plans generated by the proposed algorithm and a commonly utilized signal timing optimization software Synchro are compared in a VISSIM signal control application programming interfaces (SCAPI) simulation environment by using real filed observed traffic data. The simulation results indicate that the signal timing plan generated by the proposed algorithm is more efficient in managing over-saturated flows at intersection groups, and, thus, it has the capability of optimizing signal timing under the over-saturated conditions.

Key words: traffic signal control; optimization algorithm; intersection group; over-saturated status; NSGA-Ⅱ algorithm

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Traffic signal control evidently plays an important role in managing the urban transportation system. However, traffic control strategies under normal traffic flow conditions do not work as efficiently as necessary when the traffic demand approaches or exceeds the capacity, especially at the intersection group with coordinated signal control[1]. Since Webster[2] connected the average delay with the signal timing parameter "cycle length" and the observed traffic flow variables by using the cumulative diagram, the optimized cycle length can be calculated by minimizing the delay of the signalized intersection[2]. Similar to the Webster method, many optimization objectives are also applied in signal timing, such as minimizing cycle failures[3], minimizing stops[4] and minimizing average saturation degrees[5]. However, the algorithms listed above can hardly be utilized under over-saturated conditions.

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The traffic flow characteristics are different when the traffic flow is under the over-saturated condition or under the near-saturated condition. Under those conditions, the traffic flow becomes unstable. A small fluctuation from any vehicle in a platoon may cause adverse consequences and sharply reduce the efficiency of the traffic signal system. In the intersection group, this situation will be more serious. The intersection group is a small scale road network with several adjacent intersections which can be easily affected by each other. A route correlation degree[6] can be utilized to describe the significant level of traffic relevance. When the route correlation degree between two intersections is greater than 1, these two intersections can be considered as one intersection group. The intersection group will be easily affected by detrimental effects like residual queues and spillbacks and tend to be in a lock-out tatus[7]. Hence, a specific signal timing algorithm in connection with the characteristics of the over-saturated intersection group is needed to be established and evaluated.

1 Traffic Flow Characteristics of Over-Saturated Intersection Group

The traffic status is commonly determined by traffic intensity, i. e., the V/C ratio. The traffic status can be considered as over-saturation when the V/C ratio is greater than 1. However, the real-time traffic volume and the actual capacity are difficult to determine under the over-saturated condition. Thus, the over-saturation can be defined as the condition of an approach with a residual queue[8] at signalized intersections (see Fig. 1). As it is difficult to measure the residual queue directly, it can be estimated by the loop detector[9] information or mobile sensor[10] information by using the shockwave theory.

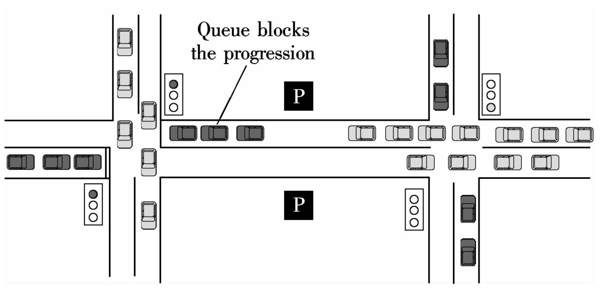

Fig. 1 Residual queues at intersection

Generally, an over-saturated condition first appears at one or several isolated intersections with a relatively high saturation degree in the intersection group. Then, the congestion begins to spread to the neighboring intersections (see Fig. 2). Furthermore, the shockwave between congestion and normal conditions will spread faster along a route with a relatively large traffic volume. Finally, the whole road network will be congested, even under a lock-out status. According to the process of congestion generation, specific traffic control strategies should be formulated to avoid the lock-out status when congestion begins to spread in the intersection group.

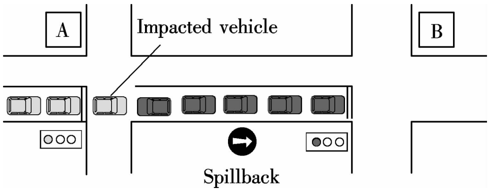

Fig. 2 Spillback at intersections

2 Algorithm Selection

2.1 Selection of optimization objectives

The principal contradiction of the over-saturated intersection group turns to a spatial conflict for the road space instead of a temporal conflict for passage right. When the road network turns into an over-saturated status, the principal task is to disperse the queues at intersection approaches to prevent residual queues and spillbacks, especially at the links with high probability to be congested. In this way, the throughput maximum for the critical route of the intersection group should be selected as one of the optimization objectives.

The queue problem is the major detrimental effect under the over-saturated condition. The signal timing optimization algorithm should obtain the capability of maintaining the queue ratio of each approach (or critical route/intersection) in an acceptable range. In this control strategy, the time of the green phase should be adjusted to balance the queues at intersection approaches under the over-saturated condition. The objective is to minimize the number of blocked intersections by maintaining the queue ratio along the critical route of the intersection group.

Based on the discussion listed above, two optimization objectives, "throughput maximum" and "queue ratio maintenance" along the critical route of the intersection group, are selected in the proposed traffic signal timing optimization algorithm.

2.2 Selection of algorithm

In order to achieve the optimization objective of "throughput maximum", the algorithm tends to extend the cycle length to avoid the lost time brought on by the phase transition process. However, the queue of the conflicted intersection approaches will form very quickly under the over-saturated condition, and get an extremely high probability to be "spillback" if the long cycle length is selected. At this time, the proposed algorithm should have the capabilities of maintaining the queue ratio at each approach to prevent the detrimental effects. In this way, throughput maximum and queue ratio maintenance are two conflicting objectives, which is a typical multi-objective optimization problem (MOP). Many intelligent algorithms, such as the evolutionary algorithm (EA), the particle swarm optimization (PSO), the simulated annealing algorithm (SA) and the ant colony optimization (ACO), can be utilized to obtain the Pareto front of the MOP. However, of all the algorithms, only the genetic algorithms (GA), one category of the evolutionary algorithm, is successfully applied in the traffic signal control system for commercial productions[11]. A non-dominated sorting genetic algorithm Ⅱ (NSGA-Ⅱ)[12] has better performance than other multi-objective evolutionary algorithms, and, thus, it is selected as the traffic signal control optimization method in this paper.

2.3 NSGA-Ⅱ algorithm

The major procedure of the NSGA-Ⅱ algorithm is shown in Fig. 3. The main loop of the NSGA-Ⅱ algorithm is listed below:

Step 1 Initially, a random parent population P_0 is created. The population is sorted based on non-domination level. Each solution is assigned a fitness (or rank) equal to its non-domination level. The usual binary tournament selection, recombination, and mutation operators are used to create an offspring population Q_0 of size N. Let $t=0$.

Step 2 A combined population $R_t = P_t \cup Q_t$ is formed. The population R_t is of size $2N$. Then, the population R_t is sorted according to non-domination. The best non-dominated set F_i is formed.

Step 3 The crowded-comparison operator $\prec_n$ is chosen to sort the non-dominated set F_i in a descending order. The best N members of the set are chosen for the new population P_{t+1}.

Step 4 The new population P_{t+1} is now used for selection, crossover and mutation to create a new population Q_{t+1}.

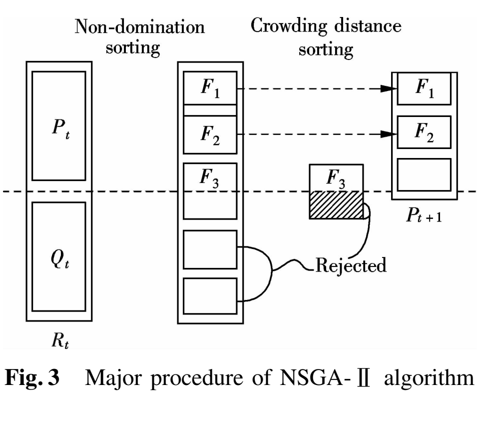

Fig. 3 Major procedure of NSGA-Ⅱ algorithm

Step 5 When the termination condition is met, the loop stops; otherwise, $t = t + 1$, and return to step 2.

3 Design of Algorithm

3.1 Coding scheme

The coding scheme has evident effects on genetic manipulation, especially for crossover. The binary encoding, real number encoding and structural encoding are three mostly used coding schemes in genetic algorithms. In the traffic signal control optimization problem, the coding scheme should obtain the capability to describe the signal timing plan. If the binary encoding is applied, additional constraints are needed in the process of crossover and mutation. Besides, the logical constraints between genes should also be considered (for example, the cycle length should be the summation of all the green times and lost times). All these constraints increase the complexity of the calculation. Hence, the real number encoding is selected as the coding scheme in the traffic signal control optimization problem. The green time of each phase is the executable genetic operator of the gene.

3.2 Optimization objective functions

Two optimization objectives, "throughput maximum" and "queue ratio maintenance" are selected in the proposed algorithm. It is assumed that high resolution traffic data are available for signal timing plan optimization. The output of the algorithm is the green time of all phases. The phase sequence is pre-defined.

Under the over-saturated condition, the traffic system is erratic, especially at the critical route of the intersection group or the the critical movement of the intersection. Hence, the primary target of traffic control under the over-saturated condition is to maintain the traffic flow in a stable state, and to discharge as many vehicles as possible, especially for the critical movement. For the purpose of maximizing the throughput vehicles of the critical movement, a weight coefficient should be multiplied by the actual throughput numbers in the corresponding optimization objective function. Thus, the throughput maximum optimization function in the algorithm can be obtained as

$$O_c = \max \sum_{i=1} \sum_{n=1} (\omega_i^n m_i^n (g_i^n, C_i, t)) \tag{1}$$

where O_c is the weighted maximum throughput vehicle number of the intersection; ω_i^n is the weight coefficient of the n-th movement at the i-th intersection; $m_i^n(g_i^n, C_i, t)$ is the actual throughput vehicles of the n-th movement at the i-th intersection, which is a function of the green time of phase g_i^n, cycle length C_i and time t. These parameters can be directly obtained from the VISSIM simulation environment in this research.

Many traffic optimization measures can be classified as the queue maintenance strategy, such as the average queue length, the maximum queue length, the maximum average queue length and the dissipated queue length. The queue occupancy ratio is utilized as the optimization objective by considering the impact of acceptable queue space. By selecting this conception as the optimization objective, the detrimental effect "spillback" can be relieved effectively. Meanwhile, the queue length of each phase can also be optimized. The queue ratio maintenance optimization function in the algorithm can be obtained as

$$O_1 = \min \sum_{i=1} \frac{1}{p_i} \sum_{p=1}^{P} \frac{l_p^i(t)}{L_p^i} \tag{2}$$

where p_i is the phase number of the i-th intersection; $l_p^i(t)$ is the queue length of the p-th phase at the i-th intersection; L_p^i is the maximum acceptable queue of the corresponding phase.

4 Evaluation Setup

4.1 Simulation environment

The proposed algorithm is deployed and evaluated in a prevailing microscopic traffic simulation environment VISSIM. The advantages of the VISSIM over other simulation packages include:

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

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

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

The VISSIM SCAPI method is used to develop the signal control emulator in this research[13]. The SCAPIs are written in C++/CLR language. The original version of the SCAPI controller requires that the signal control algorithms should 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, and then return the new desired phase states back to the VISSIM network. At each time interval, the controller runs the algorithm, makes decisions according to the current state, and then returns the new desired phase states to the VISSIM network. The concept of the simulation environment is illustrated in Fig. 4.

4.2 Experimental design

The real filed traffic data from an intersection group at the Guangzhou Road in Nanjing is selected to test the proposed traffic control optimization algorithm. The traffic

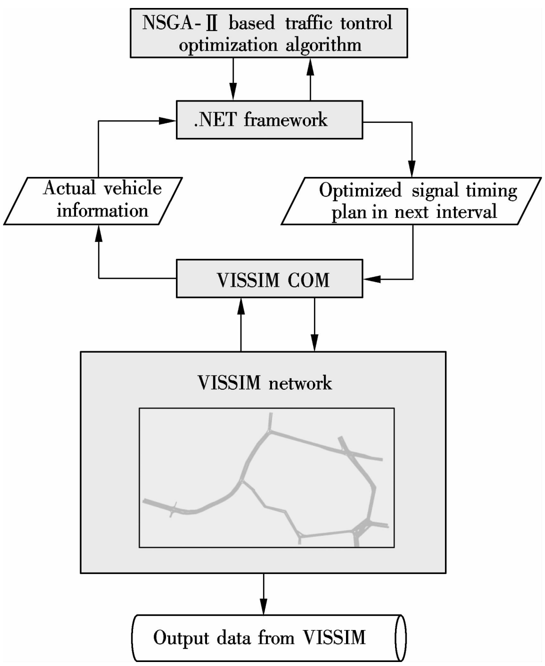

Fig. 4 Simulation environment of VISSIM

data (without pedestrian and non-motor vehicles) was collected from 7:30 am to 8:30 am on December 10th, 2009. Based on the observed traffic volume, the intersection group was under an over-saturated condition during this period. The layout of the intersection group is shown in Fig. 5. Each movement is coded by the following rules: intersection name, approach ID and turning direction (e. g., A1S means the first approach straight movement of intersection A). The critical route information used in the proposed method was previously detected by a wavelet and spectrum-based identify algorithm[14]. As shown in Fig. 6, the critical route of the Guangzhou Road intersection group contains two critical routes and two sub-critical routes. The experimental configurations are listed in Tab. 1. Within the signal timing plan, the NEMA's typical dual-ring structure[15] is utilized to achieve the purpose of adjusting the green time flexibly based on the traffic volume. The yellow and all-red phases are set at the phase switching process, which are set to be 3 s for yellow and 2 s for all red.

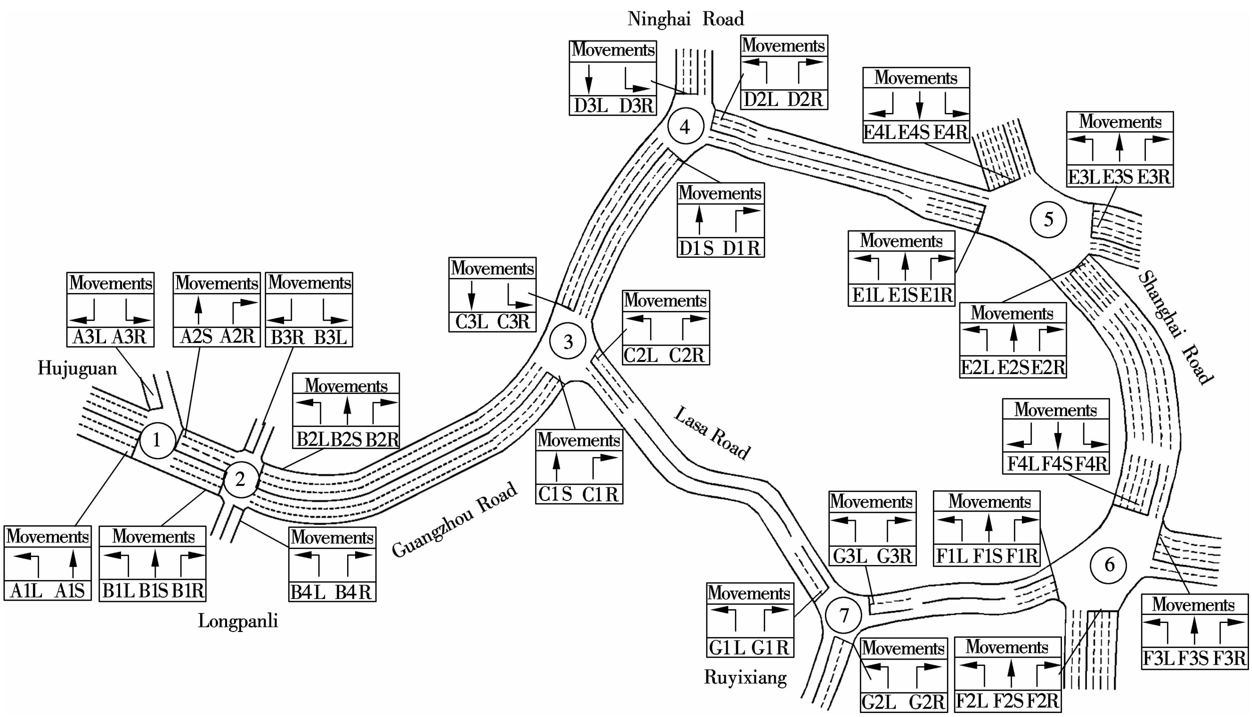

Fig. 5 Layout of the intersection group

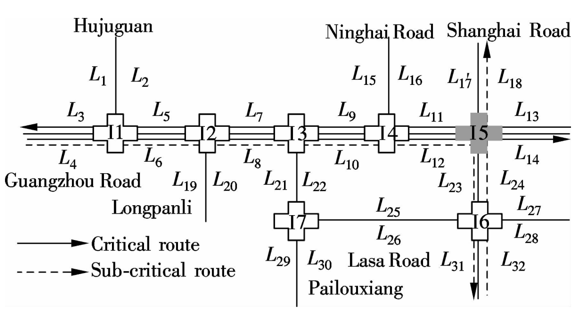

Fig. 6 Critical routes of the intersection group

Tab. 1 Experimental configurations of the proposed algorithm

Parameters	Desired value
Desired speed/ $(km \cdot h^{-1})$	60
Minimum green time/s	12
Maximum green time/s	60
Simulation time/s	3 600
Population size	200
Crossover probability	0. 8
Mutation probability	0. 1
Evolution generation	100

The coordinated timing plan generated by the Synchro software is selected as a reference to evaluate the proposed traffic control strategy. After running the proposed algorithm, the optimized signal timing plan is listed in Tab. 2. The result of the Synchro scenario is listed in Tab. 3.

Tab. 2 Optimized traffic signal timing plan by NSGA-Ⅱ algorithm

Intersection ID	Shared cycle length (142 s)				Offset
	Phase 1	Phase 2	Phase 3	Phase 4	
I1	51	51	40		126
I2	58	44	40		110
I3	52	45	45		78
I4	50	46	46		41
I5	46	28	40	28	0
I6	36	30	46	30	50
I7	56	43	43		84

Tab. 3 Optimized traffic signal timing plan by Synchro software

Intersection ID	Shared cycle length (168 s)				Offset
	Phase 1	Phase 2	Phase 3	Phase 4	
I1	60	60	48		152
I2	70	50	48		138
I3	62	53	53		85
I4	58	55	55		52
I5	55	33	48	32	0
I6	44	32	55	37	58
I7	66	51	51		89

4.3 Results and analysis

The VISSIM software has the capability of evaluating the effects of traffic control strategies under pre-defined traffic conditions. With built-in data collectors in the VISSIM, the vehicle counts of a specific point (or along a route) and the queue length of an approach can be summarized. After the simulation of the two scenarios, the evaluation parameters are summarized in Tab. 4. It is indicated that the throughput vehicles of all the intersections obtained from the NSGA-Ⅱ scenario are larger than those from the Synchro scenario, especially at the critical intersections. In this way, the traffic flow is distributed evenly along the whole intersection group. The storage capability of the road section is fully utilized to avoid the lock-out status at the critical intersection. In the NSGA-Ⅱ scenario, the queue lengths at intersections along the critical route are all smaller than those in the Synchro scenario. However, compared with the Synchro scenario, there does exist one intersection (I7) with a higher queue length in the NSGA-Ⅱ scenario. The reason for this phenomenon is that the cycle length of the Synchro scenario is longer, which leads to relatively longer queues. For the purposes of maximum throughput vehicles along the critical route, some vehicles are guided to the Lasa Road, leading to a relatively high queue length by using the signal timing plan generated by the NSGA-Ⅱ algorithm. Serious congestion occurs at intersection 2 at the end of the simulation in the Synchro scenario. It is indicated that the number of throughput vehicles drops and the queue length increases sharply. At the end of the simulation, the detrimental effect is spread to intersections 1 and 3, but has little effect on other intersections.

Tab. 4 Comparisons of the evaluation parameters between NSGA-Ⅱ algorithm and Synchro

Evaluation parameters	Throughput vehicles/veh		Average queue length/m	
	Synchro	NSGA-Ⅱ	Synchro	NSGA-Ⅱ
I1	6 884	8 345	612	366
I2	7 081	8 658	725	387
I3	7481	8 978	549	427
I4	9 659	10 226	437	415
I5	11 071	11 946	509	487
I6	10 319	10 590	427	398
I7	8 446	8 573	442	453
Total	60 941	67 316	3 701	2 933

5 Conclusion

A NSGA-Ⅱ based traffic signal timing algorithm for the intersection group with the capability of working under an over-saturated condition is proposed. Throughput maximum and average queue ratio minimum are selected as the optimization objectives of the algorithm under the over-saturated condition. Experimental results indicate that the proposed algorithm has the capability of determining effective traffic signal timing plan under the over-saturated condition. Further work should concern the on-line signal timing optimization method for the over-saturated intersection group with the consideration of the impact of pedestrian and non-motor vehicles.

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基于 NSGA-Ⅱ算法的过饱和状态交叉口群交通信号配时优化

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摘要:为提升过饱和状态下交叉口群交通信号控制的效率,提出了一种基于 NSGA-Ⅱ算法的信号配时优化方法. 交叉口群关键路径上通行车数最大及平均排队比最小被选择为过饱和状态信号配时方法的优化目标. 应用基于 VISSIM 软件信号控制程序接口的仿真环境,在输入实际观测数据的情况下,对所提算法和 Synchro 配时优化软件所生成的信号配时方案的效率进行对比. 结果表明,所提出算法生成的信号配时方案能更有效地管理过饱和状态下交叉口群的交通流,具有优化过饱和状态信号配时方案的能力.

关键词:交通信号控制;优化算法;交叉口群;过饱和状态;NSGA-Ⅱ算法

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