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Signal Cooperative Control With Traffic Supply and Demand on a Single Intersection

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ABSTRACT Traffic signal control is widely used at intersection to improve its operation efficiency. However, the existing signal control systems cannot satisfy the control requirements under unsaturated, saturated, and oversaturated conditions, which will induce queue spillover, even network deadlock. A signal Cooperative Control method with traffic Supply and Demand (CCSD) on a single intersection is put forward to maximize the efficiency and avoid queue spillover by the cooperation between traffic supply and demand. A general CCSD control framework is constructed by the control relationship description and discrete-time state-space equations. Furthermore, the uniform matrix description of CCSD is put forward under the framework to fast solve the problem by matrix calculation. An artificial intelligence planning model on CCSD is established by an objective function compromising between throughput and fairness to satisfy the control requirements under dynamic unknown traffic environment. CCSD is compared with the Webster method and capacity-aware back-pressure (CABP) control in the experiments by both the simulation data and investigation data under unsaturated, saturated, and oversaturated conditions. The results show that CCSD is superior to CABP control and the Webster method in the throughput, the number of stops, and stop time, and can avoid the queue spillover. Accordingly, CCSD can be used to improve the efficiency and avoid queue spillover at intersection under all traffic conditions.

INDEX TERMS CCSD, cooperative control, traffic supply and demand, AI planning.

I. INTRODUCTION

Traffic signal control is one of the most effective ways to improve the operation efficiency and traffic safety on intersections. In recent years, with the rapid growth of traffic flows, traffic congestion has been a serious problem in urban cities, which results in huge cost of time, money, and fuel [1]. How to optimize signal timing plan to improve the operation efficiency of intersections and alleviate traffic congestion has become a main challenge on traffic signal control system.

For several decades, plenty of researches and works have been investigated extensively on traffic signal control. Signal control systems, such as TRANSYT [2], SCATS [3], SCOOT [4], OPAC [5], [6], RHODES [7], and so on have been widely applied in practice, and many cities benefit from them. These systems aim to minimize the delay, emission of gas, queue length or maximize the throughput of intersection etc. The control parameters are optimized according to offline or online traffic flows on intersection approaches by using classical mathematical and computational methods, such as multi-objective programming [8], dynamic programming [9], [10], integer programming [11], etc. As a stochastic process, the traffic flow varies with time randomly, which will bring the uncertainty to the optimization solutions. To the traditional mathematical optimization theories, the optimization control problem on traffic flows will be a NP hard problem, which will induce the curse of dimensionality and even fail during the process of optimal control objectives solutions.

Artificial Intelligence (AI) technologies provide a fast solution to complex uncertain problems by perceiving the environments and taking actions properly. At present, many AI technologies such as genetic algorithm [12], fuzzy logic [13], multi agent, and reinforcement learning [14]–[16], and so on have been resorted to solve the traffic signal optimization problems. In these methods, the optimization problem is solved according to the traffic flow parameters on intersection approaches, such as the queue lengths, the occupancy information, or traffic volumes. Although the above methods improve the operation efficiency of intersections to some extent in theory, these methods will induce spillback when the intersection is oversaturated.

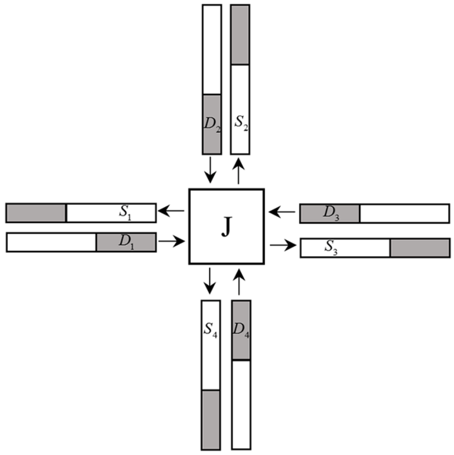

FIGURE 1. Traffic supply and demand of intersection.

In general, Traffic Demand, termed as the traffic arrivals on intersection approaches, represents the quantity of traffic flows at intersection approaches need to be discharged. However, Traffic Supply, termed as the storage capacity in the downstream of intersection, represents maximum capacity vehicles can be released in the downstream. Fig.1 shows a classical traffic demand and supply relations on an intersection, where the shadow is the queues of vehicles. Up to now, the aforementioned methods and most traffic control methods adopt the demand responsive strategy to optimize the signal parameters. Here, the control methods are called Signal Control based on Traffic Demand (SCTD). To SCTD, the demand responsive strategy is required to release the arriving traffic volumes as many as possible. Apparently, SCTD works under the assumptions that the downstream can hold all vehicles the intersection released. Once the downstream cannot hold all released vehicles, the assumptions will be invalid. When the traffic flows are unsaturated, the SCTD will satisfy the assumption and get better control results. However, when the traffic flows up to saturated or oversaturated conditions, SCTD will cause signal phase failure, which brings downstream waiting queue spillover, even network deadlock.

To avoid the queue overflow when the traffic flows belong to the saturated or oversaturated conditions, there have been extensive research efforts to develop the signal control methods. Bang-bang control is employed to solve the minimum delay problem on oversaturated intersections system with queue length constraints [17]. Queue-based quasi-optimal feedback control strategy is proposed to deal with the maximum queue constraints with the off-line optimum in the case of constant demand [18]. The boundary of waiting queue length is estimated and further minimized by a state feedback control for an oversaturated intersection in [19]. Besides, the queue length constraints control strategy is extended to road networks control through the coordination among intersection groups to alleviate traffic congestion. The signal offsets are adjusted adaptively to improve the throughput of oversaturated arterials and prevent queue spill-back [20], [21]. RT/IMPOST control policy is designed to control queue growth on every saturated approach by suitably metering traffic to maintain stable for oversaturated arterials [22]. Queue growth equalization network is developed to equalize queue growth rates across links in over-saturated urban roadway networks and thus postpones queue spillbacks that form at the localized sections of networks [23]. Although these methods aim to prevent downstream blockage by solving optimization problem subject to queue length constraints to restrain upstream input, SCTD are still employed essentially. As usual, downstream storage capability is an important index to release the upstream arrivals. Therefore the traffic supply has been taken into account to satisfy the control requirements of oversaturated conditions. Queue spillover condition is identified by analyzing the speed of vehicles at exits, and the green time will be cut off earlier if a potential queue spillover is detected [24]. A Capacity-Aware Back-Pressure control strategy (CABP) is employed by normalizing pressures according to approaches and exits' queue capacities [25]. At network level, Genetic Algorithm is used as large-scale optimization model maximizing throughput with constraints on downstream storage capability and green time utilization [26], [27].

In fact, an ideal signal control strategy should be able to cope with all the conditions of intersection in practice, including unsaturation, saturation and oversaturation. Moreover, large-scale optimization model is technically feasible but not very practical due to the complexity especially for real-time traffic control. As a primary control unit, it is important to develop a new control method satisfying all traffic conditions on a single intersection.

To satisfy the control requirements under all traffic conditions, a signal Cooperative Control method with traffic Supply and Demand (CCSD) on a single intersection is put forward in the paper. A general control framework is constructed according to CCSD's control idea and an AI planning model on CCSD is presented to solve a comprised optimization problem between the throughput and fairness. To validate the efficiency of CCSD, CCSD is compared with CABP and Webster method through simulation data and investigation data under different traffic conditions and the results show that CCSD is effective.

The rest of this paper is organized as follows. Section 2 gives a general CCSD control framework by the control relationship description, discrete-time state-space equations and the uniform matrix description. A CCSD AI planning model is presented by the form of a quintuple in section 3. Section 4 shows the compared experiments and results under different traffic conditions and the conclusions are drawn in the last section.

II. GENRRAL FRAMEWORK OF CCSD

A. DESCRIPTION OF CONTROL SYSTEM

In CCSD, the control idea is to maximize efficiency and avoid queue spillover on the intersection by the

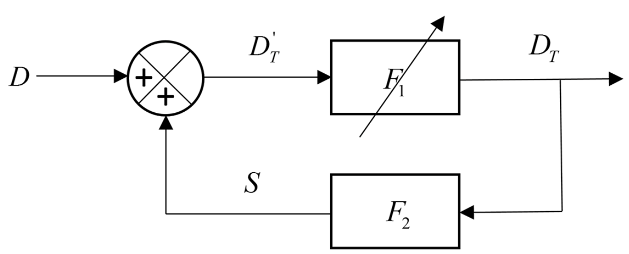

FIGURE 2. Block diagram of control system.

cooperation between traffic supply and demand. The control idea of CCSD is given as Fig.2. According to Fig.2, the inputs of CCSD system are determined by traffic supply and demand cooperatively.

Let D'_T denote the permitted transfer volume, and D'_T is expressed as (1):

$$D'_T = S \cap D, \tag{1}$$

where:

S — traffic supply;

D — traffic demand, which is determined by the waiting queue WQ and new coming volume NV in the upstream of intersection, and the traffic demand can be expressed as (2):

$$D = WQ + NV; \tag{2}$$

$\cap$ — the cooperative operation.

According to the cooperative operation, permitted transfer volume D'_T will increase if traffic supply and demand increase simultaneously. D'_T will decrease with any of traffic supply and demand reduces.

Let D_T represent the actual transfer volume, and D_T is expressed as (3):

$$D_T = F_1 (S \cap D), \tag{3}$$

where:

F_1 — traffic signal control unit which is a time delay system.

According to the control idea of CCSD, the function of F_1 is to discharge the permitted transfer volume D'_T as many as possible.

F_2 is a supply transform unit. The function of F_2 is to generate the traffic supply according to the actual transfer volume D_T, discharge volume L, and the storage capacity SC in the downstream of intersection. And the traffic supply can be expressed as (4):

$$S = F_2 (D_T) = SC + L - D_T. \tag{4}$$

In order to describe the control system clearly, the macroscopic discrete-time state-space equations of CCSD are expressed as (5)-(7).

The state equation:

$$D(t) = D(t-1) + NV(t-1) - D_T(t-1), \tag{5}$$
$$S(t) = S(t-1) + L(t-1) - D_T(t-1), \tag{6}$$

and the output equation:

$$D_T(t) = F_1 (S(t) \cap D(t)), \tag{7}$$

where:

t — current period;

$t-1$ — the signal period before t;

B. TRAFFIC SUPPLY AND DEMAND MATRIX

Here, the traffic supply and demand matrixes are established to describe the control problem uniformly and fast solve the problem by matrix calculation. The supply and demand matrixes of intersection are described as (8), (9):

$$S = [S_1, S_2, \cdots\cdots, S_N], \tag{8}$$
$$D = [D_1, D_2, \cdots\cdots, D_M], \tag{9}$$

where N is the number of exits, M is the number of traffic flow directions at intersection approaches, and S, D are both time-dependent vectors. As usual, the ordinal number of S and D are labeled separately and clockwise according to the intersection types.

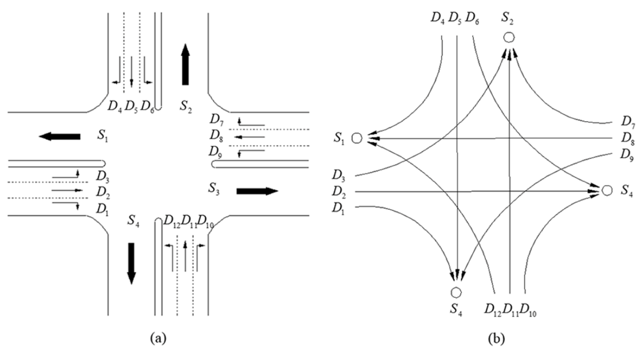

FIGURE 3. Description for traffic supply and demand on a four-way intersection. (a) Description for the relationship between traffic supply and demand and (b) description for the operation of traffic flows.

Fig.3 gives the description of traffic supply and demand on a typical four-way intersection.

The uniform matrix description of CCSD's state equation can be represented as (10), (11):

$$\begin{aligned}&[S_1, S_2, \cdots, S_N]_t \\ &= [S_1, S_2, \cdots, S_N]_{t-1} \\ &\quad - \left[S'_1, S'_2, \cdots, S'_N\right]_{t-1} + [L_1, L_2, \cdots, L_N]_{t-1},\end{aligned} \tag{10}$$

$$\begin{aligned}&[D_1, D_2, \cdots, D_M]_t \\ &= [D_1, D_2, \cdots, D_M]_{t-1} \\ &\quad - [D_{T1}, D_{T2}, \cdots, D_{TM}]_{t-1} + [NV_1, NV_2, \cdots, NV_M]_{t-1},\end{aligned} \tag{11}$$

where:

$S' = \left[S'_1, S'_2, \cdots, S'_N\right]$ — actual transfer matrix of exits, and S'_j denotes the total number of vehicles transferring to jth exit;

$L = [L_1, L_2, \cdots, L_N]$ — discharge matrix of vehicles in the downstream of intersection, and L_j represents the number of vehicles leaving jth exit;

$D_T = [D_{T1}, D_{T2}, \cdots, D_{TM}]$ — actual transfer matrix of approaches, and D_{Ti} denotes the number of vehicles transferring from ith traffic flow.

$NV = [NV_1, NV_2, \cdots, NV_M]$ — arrival matrix of vehicles in the upstream of intersection, and NV_i is the number of vehicles entering ith traffic flow.

C. DESCRIPTION FOR CONTROL MODEL

According to the control idea of CCSD, the control logic of CCSD can be represented as (12):

$$\begin{cases} [S_1, S_2, \cdots, S_N]_{t+1} - [D_1, D_2, \cdots, D_M]_{t+1} \\ \qquad \times \begin{bmatrix} tr'_{11} & \cdots & tr'_{1N} \\ \vdots & & \vdots \\ tr'_{M1} & \cdots & tr'_{MN} \end{bmatrix} \geq O \\ 0 \leq tr'_{ij} \leq 1, i \in [1, M], j \in [1, N], \end{cases} \tag{12}$$

where:

$t+1$ — the signal period after t;

$Tr' = \begin{bmatrix} tr'_{11} & \cdots & tr'_{1N} \\ \vdots & & \vdots \\ tr'_{M1} & \cdots & tr'_{MN} \end{bmatrix}$ — reachable transfer matrix, where tr'_{ij} represents the vehicles transfer proportion from ith traffic flow to jth exit under the permitted phase and tr'_{ij} is a time-dependent variable;

$O = [0, 0, \cdots, 0]$ — a zero matrix and its dimension is N;

$0 \leq tr'_{ij} \leq 1, i \in [1, M], j \in [1, N]$ is a mathematical constraint according to the traffic flows states.

III. AI PLANNING MODEL ON CCSD

A. THE FRAMNWORK OF AI PLANNING

As an important branch of artificial intelligence, AI planning [28] can automatically generate the sub-planner by revising strategy online according to dynamic unknown environment. Now, AI planning has achieved advantageous performance in autonomous robots [29], manufacturing [30], automated vehicles [31], and so on, especially in complex problem solutions.

Traffic flows are time-dependent and complex at intersection. To meet the CCSD's control requirements, an AI planning model is established as the form of a quintuple:

$$\langle Q, I, G, A, R \rangle,$$

where Q is the domain of the control problem; I denotes the initial state; G represents the goal state; A and R are action and rule sets respectively.

B. SIGNAL TIMING OPTIMIZATION MODEL

Q — domain of the control problem:

The question domain of CCSD is to reach a compromise between throughput and fairness. Generally, the maximum throughput of intersection may bring about that the traffic flows in some directions cannot be discharged for a long time due to the unbalance of traffic flows. Given the fairness, penalty function η is built to every traffic flow. Hence the compromised throughput Φ with penalty in unit time is expressed as (13):

$$\Phi = \frac{(\eta * D(C)) \times Tr'_E}{C}, \tag{13}$$

where:

$\eta = [\eta_1, \eta_2, \cdots\cdots, \eta_M]$ — the penalty matrix; and $\eta_i = f\left(T_{w,i}, L_i, H_i, K_i, \cdots\cdots\right)$ is penalty function for ith traffic flow; $T_{w,i}, L_i, H_i, K_i$ represents the waiting time, queue length, road grade, and criticality of ith traffic flow respectively;

C — the period of decision time;

$\eta * D(C)$ — the hadamard product of matrix η and $D(C)$;

$Tr'_E = \left[tr'_{E1}, tr'_{E2}, \cdots, tr'_{EM}\right]^T$ — transfer matrix of vehicles at intersection approaches, and tr'_{Ei} represents the vehicles transfer proportion of ith traffic flow; $tr'_{Ei} = \sum_{j=1}^{N} tr'_{ij}$.

According to the question domain of CCSD on compromised throughput, to formulate the optimization problem of CCSD, the signal timing optimization model can be expressed as (14).

Objective function:

$$\max \Phi = \frac{(\eta * D(C)) \times Tr'_E}{C},$$

Subject to:

$$\begin{cases} S(C) - D(C) \times Tr' \geq O \\ Tr' = Tr \wedge RM \\ 0 \leq tr_{ij} \leq 1, i \in [1, M], j \in [1, N] \\ Tr'_E = sum\left(Tr'\right) \\ g = \left(D(C) * {Tr'_E}^T\right) \times E^{-1} \\ C = combine\left(g_1, g_2, \cdots, g_M\right) \\ T_{\min} \leq g \leq T_{\max}; \end{cases} \tag{14}$$

A — action set:

$$\begin{aligned} A = \langle act_1, &act_2, \cdots, act_k, \cdots \rangle \\ act_1 &: amber\,(flow_i); \\ act_2 &: green\,(flow_i); \\ \vdots \quad & \quad \vdots \\ act_k &: red\,(flow_i); \\ \vdots \quad & \quad \vdots \end{aligned}$$

R — rule set:

$$\begin{aligned} R = \langle r_1, &r_2, \cdots, r_k, \cdots \rangle \\ r_1 &: amber\,(flow_i) = next\,(green\,(flow_i)); \\ r_2 &: amber\,(flow_i) = pre\left(green\left(flow_j\right)\right); \\ \vdots \quad & \quad \vdots \\ r_k &: ifS\,(flow_i) = 0, then\ act_k; \\ \vdots \quad & \quad \vdots \end{aligned}$$

I — initial state:

$I = \langle S_I, D_I \rangle$, where $S_I = [S_1, S_2, \cdots, S_N]_{t_0}$ represents the traffic supply at initial time t_0, and $D_I = [D_1, D_2, \cdots, D_M]_{t_0}$ represents the traffic demand at initial time t_0;

G — goal state:

the state of intersection that satisfies the objective function;

where:

$\wedge$ — operation of logic and;

$Tr_{M\times N}$ — transfer matrix, and tr_{ij} is the transfer proportion of vehicles from *ith* traffic flow to *jth* exit;

$RM_{M\times N}$ — reachable matrix from approaches to exits of the intersection; rm_{ij} is boolean, and the vehicles can transfer from *ith* traffic flow to *jth* exit when $rm_{ij} = 1$, otherwise the vehicles cannot transfer;

$g_{1\times M}$ — the matrix of green time, and g_i is the green time of *ith* traffic flow;

$E_{M\times M}$ — discharge rate matrix of vehicles on intersection approaches, and $E_{M\times M}$ is a diagonal matrix; the element on the diagonal E_{ii} is vehicle discharge rate of *ith* traffic flow;

$combine\,(g_1, g_2, \cdots, g_M)$ — the phase combination during the period of C;

$T_{\min}, T_{\max}$ — the matrix of minimum and maximum green time respectively, and $T_{\min,i}$, $T_{\max,i}$ represents the minimum and maximum permitted green time of *ith* traffic flow;

$flow_i$ — the *ith* traffic flow;

act_k — the *kth* action;

r_k — the *kth* rule;

$amber\,(flow_i)$, $green\,(flow_i)$, $red\,(flow_i)$ — indicate yellow, green, and red light for *ith* traffic flow respectively;

next — the successor;

pre — the precursor;

$S\,(flow_i)$ — traffic supply of *ith* traffic flow.

IV. EXPERIMENTS AND RESULTS

The experiments are carried out by utilizing simulation data and investigation data to validate the proposed control method. As a classical and widely used control method, Webster method [32] is chosen to compare with CCSD. CABP [25] is a state-of-the-art control method to avoid the queue spillover, and CABP is also used in the simulations. Many technologies can be used to solve the signal control optimization problem, such as genetic algorithm [33], krill herd algorithm [34]–[36], particle swarm optimization algorithm [37]. In experiments, the decision tree [9] is employed to solve the CCSD optimization problem. The CCSD optimization solution algorithm is programmed by c language on the platform of windows7 system and vc6.0 development environment.

A. EVALUATION INDEX

As usual, travel delay and throughput are chosen as the primary indexes to evaluate an intersection's operation efficiency. Here, the following indexes are used to reflect the travel delay and throughput of intersection.

1) Total throughput V during the period T;
2) average throughput $\overline{V}$ in unit time, and $\overline{V} = V/T$;
3) total stop time T_s;
4) average stop time $\overline{T}_s$, and $\overline{T}_s = T_s/(V + Q_T)$;
5) total number of stops N_s;
6) average number of stops $\overline{N}_s$, and $\overline{N}_s = N_s/(V + Q_T)$;

where Q_T is the queue length of intersection at the moment T.

B. COMPARED EXPERIMENTS USING SIMULATION DATA

CCSD is compared with Webster method and CABP by experimental simulations to validate the proposed method. The simulation is carried out at a typical four-way intersection shown in Fig.3. The phase sequence is planned as Fig.4 according to the human driving habits to simplify the phase combination computing.

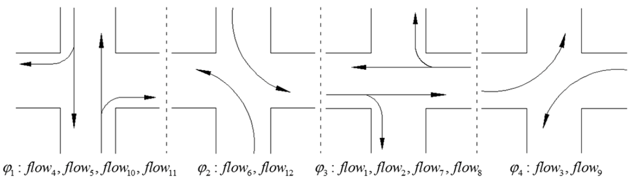

FIGURE 4. **Intersection with fixed four-phase sequence control.**

To satisfy CCSD's application, the phase combination of Fig.4 is re-modified according to the traffic states. If one of the flows in a common phase cannot be discharged, the flow's phase will be stopped earlier. If all flows in the common phase cannot be assigned, the phase will jump to the next in order. In CCSD experimental simulations, part of the rule set about phase combination is defined as follows.

$$r_1 : amber\,(flow_i) = next\,(green\,(flow_i)), \quad i \in [1, 12];$$

$$r_2 : amber\,(flow_i) = pre\,(red\,(flow_i)), \quad i \in [1, 12];$$

$$r_3 : \forall flow_i \in [flow_4, flow_5, flow_{10}, flow_{11},],$$
$$if\ S\,(flow_i) \neq 0, then merge\,(flow_i);$$
$$\forall flow_i \in [flow_6, flow_{12}],$$
$$if\ S\,(flow_i) \neq 0, then merge\,(flow_i);$$
$$\forall flow_i \in [flow_1, flow_2, flow_7, flow_8,],$$
$$if\ S\,(flow_i) \neq 0, then merge\,(flow_i);$$
$$\forall flow_i \in [flow_3, flow_9],$$
$$if\ S\,(flow_i) \neq 0, \quad then\ merge\,(flow_i);$$

$$r_4 : if S\,(flow_i) = 0, \quad then\ red\,(flow_i);$$

$$r_5 : next\,(flow_{10}, flow_{11}) = flow_{12};$$
$$next\,(flow_4, flow_5) = flow_6;$$

TABLE 1. Rates of approaches arrivals under different conditions.

Traffic flow	1	2	3	4	5	6	7	8	9	10	11	12
Unsaturation (veh/s)	0.06	0.09	0	0.05	0.10	0	0.04	0.11	0	0.04	0.12	0
Saturation (veh/s)	0.02	0.11	0	0.10	0.23	0	0.03	0.10	0	0.09	0.21	0
Oversaturation (veh/s)	0.05	0.13	0	0.13	0.31	0	0.07	0.10	0	0.12	0.30	0

$$next\ (flow_{12}) = flow_7, flow_8;$$
$$next\ (flow_6) = flow_1, flow_2;$$
$$next\ (flow_7, flow_8) = flow_9;$$
$$next\ (flow_1, flow_2) = flow_3;$$
$$next\ (flow_9) = flow_4, flow_5;$$
$$next\ (flow_3) = flow_{10}, flow_{11};$$
$$r_6 : if\ merge\left(flow_i, flow_j \cdots\right),$$
$$then\ g_{i,start} = g_{j,start} = \cdots, g_{i,end} = g_{j,end} = \cdots;$$

where traffic flow is labeled clockwise as shown in Fig.3; $merge\left(flow_i, flow_j \cdots\right)$ represents that $flow_i, flow_j \cdots$ share a common phase; $g_{i,start}$ and $g_{i,end}$ denote the start and end of the green time for *ith* traffic flow respectively.

During the process of simulation, we assume that:

(1) There is no start-up lost time for vehicles, and the capacity is set as 1600 vehicles/lane per hour on saturated conditions for the clear time losing.

(2) The amber time is 2s.

(3) The minimum green time is 6s, and the maximum green time is 60s.

(4) Approaches arrivals satisfy with a Berboulli probability distribution.

(5) The right-turn volume is 0.

The simulation experiments are carried out to compare Webster method, CABP with CCSD for 15 minutes under unsaturated, saturated, and oversaturated conditions respectively. The rates of approaches arrivals under the three conditions are shown in Table.1. Table.2-6 and Fig.5-7 give the compared results of CCSD, CABP and Webster method. From Table.2, it can be shown that the spillback occurred using the Webster method under saturated or oversaturated conditions. Hence, the simulation experiments on Webster method were not assigned under oversaturated conditions.

TABLE 2. Queues overflow or not under different control methods.

Traffic condition	Unsaturation	Saturation	Oversaturation
Webster	×	√	√
CABP	×	×	×
CCSD	×	×	×

Table.3-4 and Fig.5-6 shows the stop time and the number of stops using T_s, $\overline{T}_s$, N_s, $\overline{N}_s$ under different conditions. From Table.3-4 and Fig.5-6, the indexes of T_s, $\overline{T}_s$, N_s, $\overline{N}_s$ are smaller for CCSD compared with CABP and Webster method. It can be seen that the travel delay of CCSD is smallest among the three methods under the same traffic condition.

The total throughput and average throughput are illustrated in Table.5 and Fig.7 under the three traffic circumstances. As is shown by Table.5 and Fig.7, the throughput is similar to each other under unsaturated condition. And when the intersection is saturated, CCSD is superior to the others. Especially in the oversaturation condition, CCSD does not bring about the spillback and it is better than CABP in the throughput.

To describe the comprehensive compared results better, Table.6 gives the improvements of evaluation indexes in CCSD relative to CABP and Webster method. From Table.6, it can be seen that the average stop time and average number of stops decrease greatly to CCSD, especially the decrease of average stop time and average number of stops are more than 35% and 50% respectively under unsaturated conditions. Moreover, to CCSD the average stop time decreases by 38.7% and 25.2%, the average number of stops decreases by 35.4% and 66.5%, and the average throughput increases by 15.2% and 1.8% under saturated conditions. Furthermore, when the intersection is oversaturated, the average stop time and average number of stops are both reduced, and the average throughput is increased in CCSD compared with CABP. From the compared results on travel delay and throughput, the CCSD is superior to the Webster method and CABP. In addition, CCSD can avoid the spillback under saturated and oversaturated conditions.

C. COMPARED EXPERIMENTS USING INVESTIGATION DATA

Additionally, in order to verify the control effects of CCSD in practice, traffic flows data was investigated from the intersection located at TongZhi Street - XiKang Road intersection in Changchun China. Fig.8 gives the intersection's satellite imagery and geometry.

To the intersection, the spillback occurs frequently at the direction of TongZhi Street under saturated and oversaturated conditions. Fixed time control is adopted in the intersection and the existing signal plan is optimized by Webster method. Fig.9 and Fig.10 show the existing signal plan.

TABLE 3. Total stop time and average stop time under different conditions.

Traffic condition	Unsaturation		Saturation		Oversaturation	
Evaluation index	T_s (s)	$\overline{T}_s$ (s/veh)	T_s (s)	$\overline{T}_s$ (s/veh)	T_s (s)	$\overline{T}_s$ (s/veh)
Webster	15676	27.31	70072	83.02		
CABP	14514	25.29	57360	67.96	221346	190.82
CCSD	**9308**	**16.22**	**42914**	**50.85**	**192156**	**165.65**

TABLE 4. Total number of stops and average number of stops under different conditions.

Traffic condition	Unsaturation		Saturation		Oversaturation	
Evaluation index	N_s (times)	$\overline{N}_s$ (times/veh)	N_s (times)	$\overline{N}_s$ (times/veh)	N_s (times)	$\overline{N}_s$ (times/veh)
Webster	827	1.44	1268	1.5		
CABP	1409	2.45	2446	2.9	6334	5.46
CCSD	**396**	**0.69**	**819**	**0.97**	**2466**	**2.13**

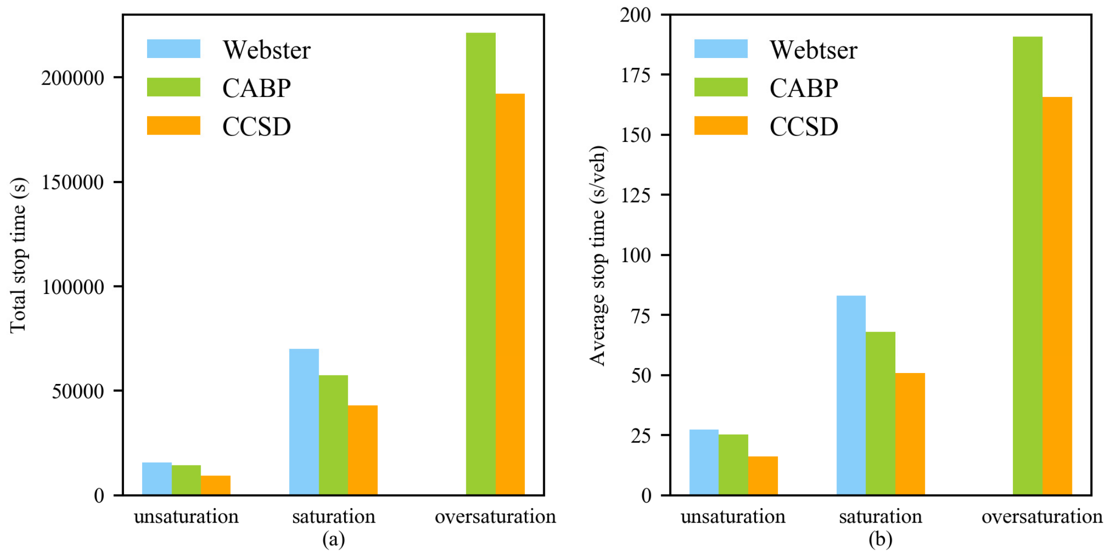

FIGURE 5. Comparison of stop time under all traffic conditions. (a) Total stop time and (b) average stop time.

TABLE 5. The total throughput and average throughput under different conditions.

Traffic condition	Unsaturation		Saturation		Oversaturation	
Evaluation index	V (veh)	$\overline{V}$ (veh/s)	V (veh)	$\overline{V}$ (veh/s)	V (veh)	$\overline{V}$ (veh/s)
Webster	556	0.618	677	0.752		
CABP	563	0.626	766	0.851	764	0.849
CCSD	**568**	**0.631**	**780**	**0.867**	**826**	**0.918**

TABLE 6. The improvements of evaluation indexes in CCSD relative to CABP and Webster method.

Traffic condition	Unsaturation			saturation			Oversaturation		
Evaluation index	$\overline{T}_s$	$\overline{V}$	$\overline{N}_s$	$\overline{T}_s$	$\overline{V}$	$\overline{N}_s$	$\overline{T}_s$	$\overline{V}$	$\overline{N}_s$
Webster	-40.6%	2.2%	-52.1%	-38.7%	15.2%	-35.4%			
CABP	-35.9%	1.0%	-71.9%	-25.2%	1.8%	-66.5%	-13.2%	8.1%	-61.4%

To get the traffic flow information, camera investigation method was used for hours during the morning rush hours. From the cameras, some time slices are selected when overflow occurred. And time of the slice lasts for 15 minutes. Some traffic flow parameters on the intersection were collected from the time slices, such as the throughput, stop time,

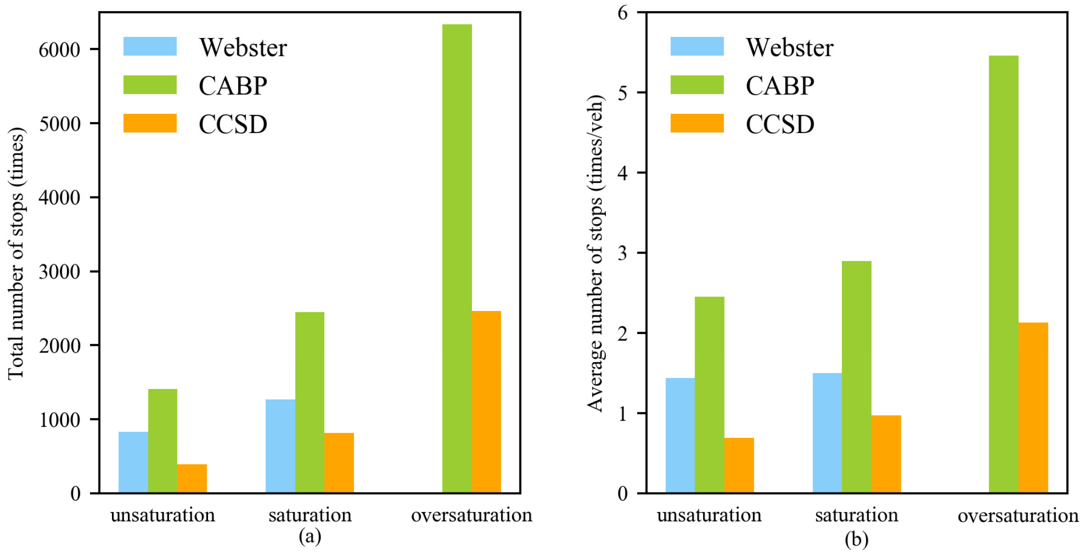

FIGURE 6. Comparison of the number of stops under all traffic conditions. (a) Total number of stops and (b) average number of stops.

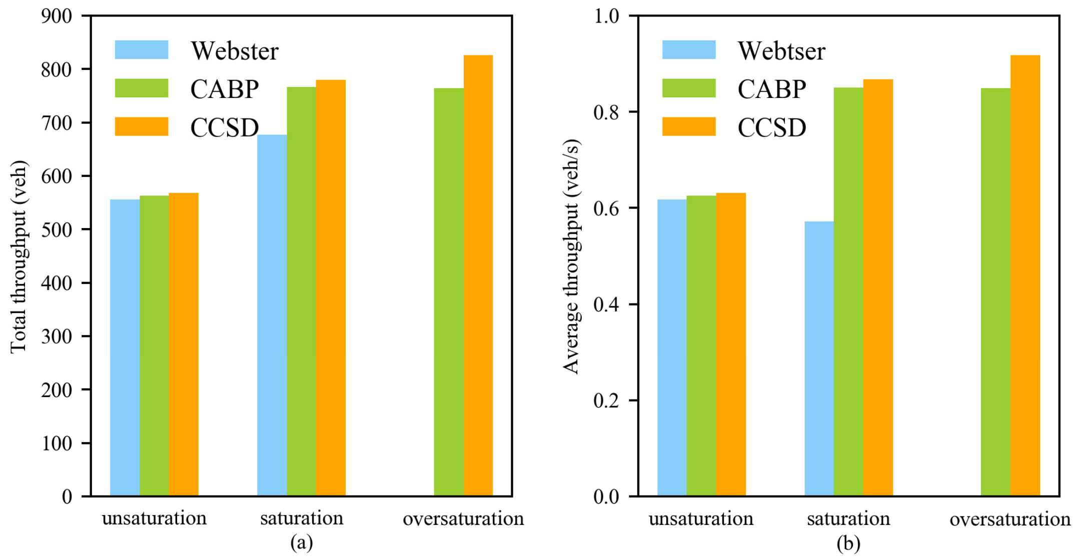

FIGURE 7. Comparison of the throughput under all traffic conditions. (a) Total throughput and (b) average throughput.

TABLE 7. The experiment results for the intersection of TongZhi Street and XiKang Road.

Evaluation index	T_s (s)	$\overline{T}_s$ (s/veh)	V (veh)	$\overline{V}$ (veh/s)	N_s (times)	$\overline{N}_s$ (times/veh)
Existed plan	21104	49.89	394	0.438	1072	2.53
CCSD	**15133**	**35.78**	**408**	**0.453**	**400**	**0.95**

number of stops, arrivals time of each vehicle in the upstream, departure time of each vehicle in the downstream and so on.

The evaluation indexes of T_s, $\overline{T}_s$, V, $\overline{V}$, N_s, $\overline{N}_s$ on exiting signal plan were collected from the video slices. And CCSD's simulation experiment was implemented for 15 minutes by using relevant traffic flow parameters, such as the arrivals time of each vehicle in the upstream, departure time of each vehicle in the downstream and so on. Furthermore, the spill-back did not happen during CCSD's simulation experiments. And the compared results on CCSD and existing signal plan are given in Table.7.

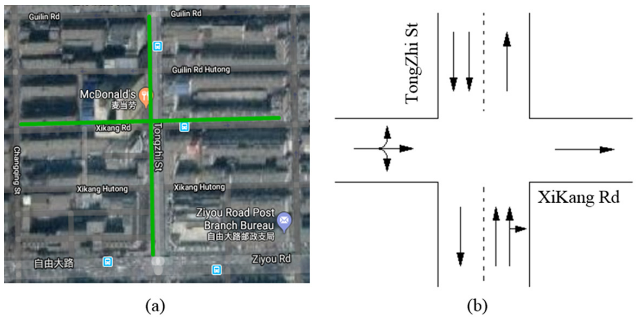

FIGURE 8. The intersection of TongZhi Street and XiKang Road. (a) The satellite imagery and (b) the geometry.

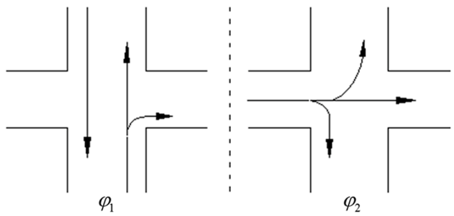

FIGURE 9. Existing phase for the intersection of TongZhi Street and XiKang Road.

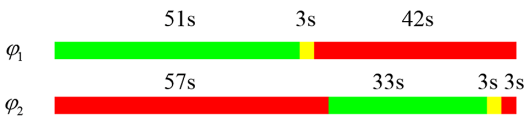

FIGURE 10. Existing timing plan for the intersection of TongZhi Street and XiKang Road.

According to Table.7, to CCSD, average throughput increases by 3%, average stop time and average number of stops decrease by 28% and 62% respectively compared with the existing signal plan. It can be seen that CCSD can not only avoid the queue overflow of intersection, but also CCSD is superior to the existing signal plan. Accordingly CCSD is effective in practice and could satisfy the control requirements under all traffic conditions.

V. CONCLUSIONS

This paper presented a signal cooperative control method with traffic supply and demand on a single intersection (CCSD) to satisfy application under all traffic conditions and avoid the queue spillover. In the proposed method, a general control framework is constructed according to CCSD's control idea. The uniform matrix representations of CCSD are put forward to fast solve the problem by matrix calculation. Considering that AI planning can generate planning and scheduling automatically under dynamic unknown traffic environment, AI planning is introduced to solve CCSD optimization problem and a quintuple AI planning model is constructed. In the AI planning model, the domain question is to reach a compromise between throughput and fairness by the penalty function.

The experiments are carried out by utilizing simulation data and investigation data to validate the proposed control method. In the experiments, CCSD is compared with Webster method and CABP. The results show that CCSD is superior to Webster method and CABP in travel delay and throughput. Furthermore, CCSD can avoid queue spillover and satisfy the control requirements under unsaturated, saturated and oversaturated conditions.

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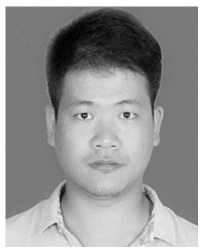

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