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Krill Herd Algorithm for Signal Optimization of Cooperative Control With Traffic Supply and Demand

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ABSTRACT As a novel signal control method, signal Cooperative Control with traffic Supply and Demand (CCSD) is superior to the traditional control methods and could satisfy the control requirements under all traffic conditions. However, the optimization solution of CCSD cannot meet the real-time control requirement for its exhaustive search. To overcome the problem, in this paper, the optimization problem of CCSD is reconstructed by the time-varying traffic supply and demand, and the problem is reduced as a problem of space search. Then, the krill herd (KH) algorithm is introduced and employed to realize the fast solution of CCSD (named KH-CCSD). During the process of optimization, the search space representation and fitness function for the KH algorithm are constructed to satisfy the solution of CCSD. The optimal signal timing plan is obtained by an iterated search of krill swarm in a multi-dimensional time-varying space cooperatively constrained by traffic supplies and demands. The convergence and effectiveness of KH-CCSD are validated by comparing experiments, in which the convergence of KH-CCSD is tested by different initializations and KH-CCSD is compared with the Webster method and capacity-aware back-pressure (CABP) control under unsaturated, saturated, and oversaturated conditions. The experiments results show that KH-CCSD performs a fast convergence and KH-CCSD is superior to the Webster method and CABP. As a result, KH-CCSD could satisfy the application of CCSD under all traffic conditions.

INDEX TERMS KH-CCSD, krill herd algorithm, signal cooperative control, traffic supply and demand.

I. INTRODUCTION

As a basic unit of road network, intersection is crucial to the operation efficiency of road networks. Traffic signal control is an important way to improve the operation efficiency of intersection. At present, many researches are carried out to determine appropriate timing plan for intersections, and TRANSYT [1], SCATS [2], SCOOT [3], OPAC [4], [5], RHODES [6] etc. have been widely used in urban cities. Although these researches and applications improve intersections' operation efficiency to some extent, queue spillback, even deadlock occurs frequently at intersections when traffic flows up to saturation or oversaturation. To avoid queue spillback, many control methods [7]–[11] have been developed under saturated and oversaturated conditions. However, the above methods are completely based on the traffic demand of intersection, termed as Signal Control based on Traffic Demand (SCTD). In other words, SCTD is developed under the assumption that the downstream of intersection have infinite capacity. Once the assumption fails, SCTD will not work. Aiming at this problem, the downstream capacity of intersection (termed as traffic supply) is taken into account, such as traffic gating/metering control [12], [13], Capacity-Aware Back-Pressure (CABP) control [14], coordinated control of arterials [15] and so on. In order to coordinate traffic supply and demand, CCSD [16] (signal Cooperative Control with traffic Supply and Demand) was proposed recently by our research team, in which traffic supplies and demands are taken as integration and cooperate with each other, and it could satisfy the control requirements under unsaturated, saturated and oversaturated conditions.

In CCSD, the optimization solution on control objective determines its performance. Generally, the optimization of CCSD is an M-N planning problem of traffic supplies and demands. And it will be a NP hard problem to the traditional mathematical optimization theories. Furthermore, traffic flows vary with time at intersection, and this will induce the time variation of traffic supply and demand, which increases the difficulty of CCSD's optimization solution. Although many optimization methods have been presented to solve the signal control problems (e.g. linear programming [17], [18], dynamic programming [4], [6], [19], [20], reinforcement learning [21]–[23]), the optimization methods are essentially used for the solution of SCTD. During the solution of SCTD optimization problem, traffic demand is only considered. Obviously, these methods cannot be used directly for the optimizing of CCSD. Furthermore, the solution of CCSD is more complex than SCTD for the cooperation between time-varying traffic supply and demand. Accordingly, the optimization problem of CCSD should be studied in advanced.

To realize the fast solution of CCSD, in this paper, the optimization problem of CCSD is reconstructed by the time-varying traffic supply and demand and the problem is reduced as a search optimization problem in a multi-dimensional space cooperatively restricted by traffic supplies and demands. As a new superior algorithm for solving global and large-scale optimization problems, Krill Herd (KH) algorithm [24] is introduced and employed to realize the fast solution of CCSD, which is termed as KH-CCSD. In KH-CCSD, the search space representation and fitness function for KH algorithm are constructed to satisfy the objective and constraints of CCSD. Then the optimal signal plan of CCSD is obtained by the search of krill swarm in the multi-dimensional space. The convergence and effectiveness of KH-CCSD is validated under all traffic conditions in the experiments. And the results showed that KH-CCSD is effective.

The rest of this paper is organized as follows. Section 2 provides related works about the optimization solution of traffic control problem including SCTD and CCSD, and the development and application of KH algorithm. Section 3 gives the control problem description of CCSD. The optimization solution of CCSD by KH algorithm is described in section 4. Section 5 shows the experiment results, and conclusions are drawn in the last section.

II. RELATED WORKS

The optimization solution of signal control problem is the core content in signal control system, and it has been researched extensively in the past decades. For example, traditional mathematical methods (e.g. linear program [17], [18], dynamic program [4], [6], [19], [20], stochastic program [25]–[27], etc.) have been widely used for signal optimization, but they are computationally intensive, and may induce the curse of dimensionality when dealing with complex and large-scale signal control problems. In recent years, the rapid development of artificial intelligence (AI) provides great opportunities in developing more efficient signal optimization solution methods. Swarm intelligence approach [28] was proposed to find successful cycle programs of traffic lights and performs a fast converge to the optimal signal timing plan. Genetic algorithm approach [29] was employed to reduce vehicles travel time and improve the reliability of travel time by identifying optimal multicriteria signal control strategies. In order to overcome the dynamic uncertainty in arterial traffic, fuzzy control method [30] is adopted to allocate green time for each intersection and enlarge green wave band. Furthermore, reinforcement learning [22], multi-agent technologies [23] and deep neural network [21] are utilized effectively to develop the traffic signal control approaches capable of learning and decision-making. However, most of these researches are based on SCTD. Although these optimization methods provide efficient solution for SCTD, they cannot meet the control requirements under all traffic conditions for lacking the consideration of traffic supply.

As a novel control style, CCSD, proposed by our research team, realizes the cooperation between traffic supply and demand, and decision tree was used to solve the optimization problem [16], but the optimization process of decision tree cannot meet the real-time requirements of signal control system for exhaustive search. Due to the cooperation between multi-road time-varying traffic supplies and demands, the optimization problem of CCSD will be a time-varying M-N mathematical programming problem. Obviously, the solution of CCSD is more complex than that of SCTD. Although many methods are used to solve the optimization problem of SCTD, they cannot be directly used for the optimization of CCSD. To meet the control requirements with time-varying traffic supplies and demands, a fast and large-scale optimization algorithm for the solution of CCSD should be researched in advanced

As a large-scale, fast and global optimization algorithm, KH is proposed based on the simulation of the herding of the krill swarms in response to specific biological and environmental processes and it has been proven to have a better performance with some existing optimization algorithm (e.g. evolutionary strategy, differential evolution, particle swarm optimization, genetic algorithm, ant colony optimization, etc.) [24]. To satisfy different objective and application, KH algorithm has been extended in recent years, such as chaotic-based KH algorithm [31], fuzzy-based KH algorithm [32], discrete-based KH algorithm [33] and so on. For its noticeable advantages in term of simplicity, flexibility, computationally efficiency, KH algorithm has been extensively used in many fields (e.g. clustering technology [34], power system [35], neural network training [36], etc.). Although KH algorithm has got superior performance in many fields, it has not been attempted in traffic signal control field.

As a superior swarm algorithm for solving global and large-scale optimization problems, KH algorithm would be more suitable for solving the optimization of CCSD than the other methods. Therefore, KH algorithm should be investigated for solving the optimization problem of CCSD in advanced.

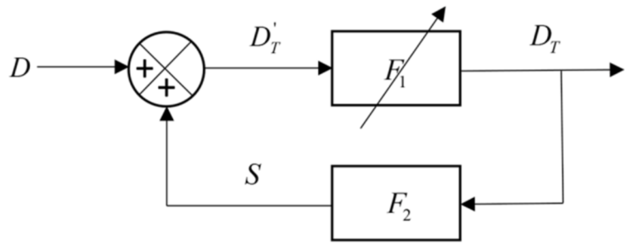

FIGURE 1. Block diagram of CCSD control system.

III. CONTROL PROBLEM DESCRIPTION OF CCSD

A. CONTROL IDEA OF CCSD

According to the description of CCSD in [16], multi-road traffic supplies and demands are taken as integration and cooperate with each other in the control system to maximize efficiency and avoid queue spillover on the intersection, and the control system of CCSD is depicted in Fig.1.

The variables in Fig.1 are represented as follows:

D — traffic demand, i.e. vehicles need to be released at intersection approaches;

S — traffic supply, i.e. the storage capacity at the downstream of intersection;

D'_T — permitted transfer volume;

D_T — actual transfer volume;

F_1 — traffic signal control unit;

F_2 — supply transform unit, generating traffic supply according to the released vehicles of downstream, residual storage capacity of downstream and actual transfer volume.

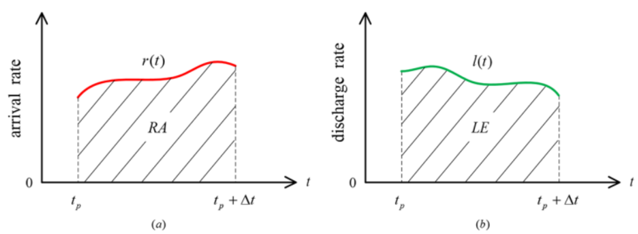

FIGURE 2. Vehicles arrival and discharge process. (a) Vehicles arrival process at approach and (b) vehicles discharge process at downstream.

B. TIME-VARYING MODEL OF TRAFFIC SUPPLY AND DEMAND

Traffic demand and supply are influenced by the arrived vehicles at approach and discharged vehicles at downstream. In fact, vehicles arrival and discharge at intersection is a time-varying process, and vehicles arrival rate at approach and discharge rate at downstream can be represented as $r(t)$, $l(t)$ respectively. Then vehicles arrived volume RA and discharged volume LE at Δt interval are the shadow in Fig.2, and RA and LE can be calculated by using (1).

$$\begin{cases} RA = \int_{t_p}^{t_p+\Delta t} r(t)dt \\ LE = \int_{t_p}^{t_p+\Delta t} l(t)dt, \end{cases} \tag{1}$$

As a result, the time-varying model of traffic supply and demand can be expressed as (2).

$$\begin{cases} D(t_c+\Delta t) = QA(t_c) + \int_{t_c}^{t_c+\Delta t} r(t)dt \\ S(t_c+\Delta t) = SC - QE(t_c) + \int_{t_c}^{t_c+\Delta t} l(t)dt, \end{cases} \tag{2}$$

where:

t_c — current moment;

$D(t_c+\Delta t)$ — traffic demand from t_c to $t_c+\Delta t$;

QA — the number of queuing vehicles at approach;

$S(t_c+\Delta t)$ — traffic supply from t_c to $t_c+\Delta t$;

SC — static storage capacity at downstream;

QE — the number of queuing vehicles at downstream.

C. OPTIMIZATION PROBLEM OF CCSD

According to control idea of CCSD, the optimization model of CCSD at a multi-way intersection is expressed as (3) to achieve the optimization control objective of compromise between throughput and fairness.

Objective function:

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

Subject to:

$$\begin{cases} S(C) - D(C) \times Tr' \geq O_1 \\ 0 \leq tr'_{ij} \leq 1, i \in [1, M], j \in [1, N] \\ Tr'_E = sum\left(Tr'\right) \\ g = \left(D(C)^* Tr'^T_E\right) \times E^{-1} \\ combine\,(g_1, g_2, \cdots, g_M, I) \leq C \\ g \in [T_{\min}, T_{\max}] \cup O_2, \end{cases} \tag{3}$$

where:

Φ — the throughput of intersection in unit time;

$\eta = [\eta_1, \eta_2, \cdots\cdots, \eta_M]$ — the penalty matrix; η_i denotes the penalty for *ith* traffic flow and η_i is decided by the waiting time, queue length, road grade of *ith* traffic flow and so on;

$D = [D_1, D_2, \cdots\cdots, D_M]$ — demand matrix; M is the number of traffic flow directions at intersection approaches and D_i represents traffic demand of *ith* traffic flow;

$\eta^* D(C)$ — 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; $tr'_{Ei} = \sum_{j=1}^{N} tr'_{ij}$;

C — the length of decision time;

$S = [S_1, S_2, \cdots\cdots, S_N]$ — supply matrix; N is the number of exits and S_j represents traffic supply of *jth* exit; generally, S and D are labeled separately and clockwise;

$Tr'_{M\times N}$ — reachable transfer matrix, where tr'_{ij} represents the vehicles transfer proportion from *ith* traffic flow to *jth* exit and tr'_{ij} is a time-dependent variable;

$O_1 = [0, 0, \cdots, 0]$ — a zero matrix and its dimension is N;

$g_{1\times M}$ — 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;

$combine\,(g_1, g_2, \cdots, g_M, L) \le C$ — decision time C is a combination of green time for all flows and the yellow time I, and the inequality is useful in cases of intersection congestion to allow for all-red stages;

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

$O_2 = [0, 0, \cdots, 0]$ — a zero matrix and its dimension is M;

$\cup$ — the union operation of sets.

IV. KH ALGORITHM OPTIMIZATION FOR CCSD

To solve the optimization problem of CCSD, the problem is reduced as a search optimization problem, and KH algorithm is introduced to search the optimal solution in the time-varying multi-dimensional space cooperatively constrained by multi-road traffic supplies and demands. In order to satisfy the search for krill swarm, the search space representation and fitness function of KH algorithm are constructed according the CCSD.

A. BASIC KH ALGORITHM

In KH algorithm, krill individuals aim to achieve the shortest distance from food and high density of the herd, and the movement of krill individual is determined by forging activity, physical diffusion, and motion induced by other krill individuals. In order to describe the motion process of krill individual, the Lagrangian model of krill individual's movement is expressed as (4) – (6).

$$X_i\,(t+\Delta t) = X_i\,(t) + \Delta t \frac{dX_i}{dt}, \tag{4}$$

$$\frac{dX_i}{dt} = N_i + F_i + D_i, \tag{5}$$

$$\begin{cases} N_i = N^{\max}\alpha_i + \omega_n N_i^{old} \\ F_i = V_f \beta_i + \omega_f F_i^{old} \\ D_i = D^{\max}\left(1 - \dfrac{ite}{ITE}\right)\delta, \end{cases} \tag{6}$$

where:

X_i — the position of *ith* krill individual;

N_i — motion induced by other krill individuals;

F_i — forging motion;

D_i — physical diffusion;

Δt — scale factor of speed vector, and it completely depends on the search space;

$N^{\max}$ — maximum induced speed;

α_i — direction of motion induced;

ω_n — inertia weight of the motion induced last time N_i^{old};

V_f — forging speed;

β_i — direction of forging motion;

ω_f — inertia weight of last forging motion F_i^{old};

$D^{\max}$ — maximum diffusion speed;

δ — a random directional vector with its elements belonging to $[-1, 1]$;

ite, ITE — actual iteration number and maximum iteration number.

In order to achieve the optimal objective, krill individuals' movements are guided by the fitness function, and the positions of krill individuals are updated iteratively in the search space in KH algorithm.

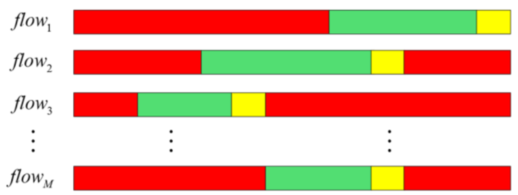

FIGURE 3. Traffic control plan for intersection.

B. SEARCH SPACE REPRESENTATION FOR KRILL SWARM

To any signal control systems, it will provide a suitable traffic control plan as shown in Fig.3. From Fig.3, it can be seen that the phase combination and green time should be given in the traffic control plan. To satisfy the control requirements, optimal phase combination and green time in traffic control plan should be given in CCSD. To represent the phase combination and green time, the solution space of CCSD can be represented as (7).

$$G = \begin{bmatrix} t_1, t_2, \cdots, t_M \\ g_1, g_2, \cdots, g_M \end{bmatrix}, \tag{7}$$

where t_i is the start time of green lights for *ith* traffic flow and g_i is the green time for *ith* traffic flow.

According to the optimization problem of CCSD, the constraints of (3) include cooperative constraint and green time constraint, where reachable transfer matrix, as an important parameter of CCSD, is determined by the green time and headway of vehicles. To satisfy the control requirements of CCSD, the search space G should be constrained by (8).

$$\begin{cases} \forall t_i, \quad g_i \in G,\ g_i = f\left((S(t_i+g_i) \cap D(t_i+g_i))\right) \\ S(t_i+g_i) = SC - QE(t_0) + \displaystyle\int_{t_0}^{t_i+g_i} l(t)dt \\ D(t_i+g_i) = QA(t_0) + \displaystyle\int_{t_0}^{t_i+g_i} r(t)dt \\ \forall g_i \in G, \quad g_i = 0\ OR\ T_{\min,i} \le g_i \le T_{\max,i}, \end{cases} \tag{8}$$

where $\cap$ denotes the cooperative operation and t_0 is the start time of signal cycle; the green time g_i must be between $T_{\min,i}$ and $T_{\max,i}$, or g_i can be set as 0 to skip *ith* traffic flow. In (8), the first three constraints represent the cooperative constraint in (3), and the last one constraint represents green time constraint in (3).

C. FITNESS FUNCTION

In KH algorithm, fitness function is used to guide the motion selection of krill individuals and determine the stopping criterion of iteration. To realize the control objective of CCSD, the compromised throughput of intersection in unit time is chosen as the fitness function to evaluate traffic control plans. The fitness function F can be expressed as (9).

$$\begin{cases} F = \dfrac{\sum_{i=1}^{M} \eta_i LA_i}{\max(t_i + g_i) + I - t_0} \\ LA_i = \min\left(D_i, S_i, \dfrac{g_i}{h}\right), \end{cases} \tag{9}$$

where LA_i is the released volume of ith traffic flow during green time and h denotes the headway. Due to the constraint of traffic supply, traffic demand and green time, the released volume LA_i should be the minimum among D_i, S_i and g_i/h; besides the length of signal cycle can be calculated by $\max(t_i + g_i) + I - t_0$.

V. EXPERIMENTS AND RESULTS

The convergence and effectiveness of KH-CCSD is validated by simulation experiments under unsaturated, saturated and oversaturated conditions. First, different initializations of krill swarm under the three traffic condition are set to evaluate the convergence. Furthermore, KH-CCSD is compared with Webster method [37] and CABP [14] under unsaturated, saturated and oversaturated conditions to evaluate the effectiveness.

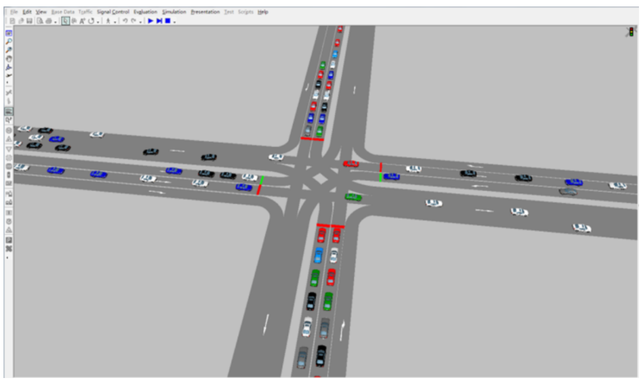

FIGURE 4. The simulation interface of VISSIM.

VISSIM simulation package with Component Object Model (COM) is used to conduct the simulation experiments, as shown in Fig.4. KH-CCSD algorithm is programmed by python language on the platform of windows7 system and PyCharm environment. Matlab (R2014b) is used to code the vehicular arrival model and realize the interaction between KH-CCSD controller and VISSIM.

A. EXPERIMENTS SETUP

The experiments are conducted at a typical four-way intersection, as depicted in Fig.5. Fig.6 gives the phase sequence which is consistent with human driving habits, and the signal timing plan for a typical four-way intersection is expressed as (10). The parameters of KH algorithm (e.g. N, ω_n, V_f, etc.) affect the convergence and efficiency

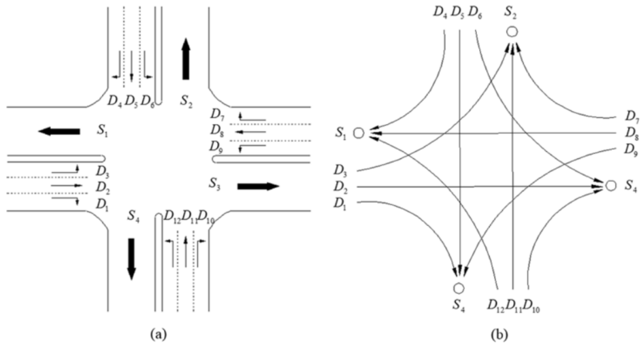

FIGURE 5. Description of traffic supply and demand on a typical four-way intersection.

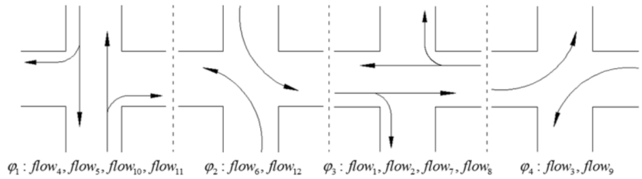

FIGURE 6. The phase sequence of intersection.

of KH-CCSD, and the parameters selection have been discussed in [24], [32], and [38]. In order to get better results, the optimal parameters of KH algorithm are set according to the discussion. Furthermore, the parameters of CCSD (e.g. minimum green time, maximum green time, etc.) are set in accordance with practice experience. And then these parameters of KH-CCSD are set as Table.1.

$$G = \begin{bmatrix} t_1, t_2, \cdots, t_{12} \\ g_1, g_2, \cdots, g_{12} \end{bmatrix}, \tag{10}$$

where:

$$t_4 = t_5 = t_{10} = t_{11} = t_0;$$
$$t_6 = t_{12} = \max(t_4 + g_4, t_5 + g_5, t_{10} + g_{10}, t_{11} + g_{11}) + I;$$
$$t_1 = t_2 = t_7 = t_8 = \max(t_6 + g_6, t_{12} + g_{12}) + I;$$
$$t_3 = t_9 = \max(t_1 + g_1, t_2 + g_2, t_7 + g_7, t_8 + g_8) + I.$$

The simulation experiments are carried out for 1800s under unsaturated, saturated and oversaturated conditions. The oversaturated condition is defined as one that the combined arrival rate at approaches exceeds the maximum throughput of intersection [7]. And when the combined arrival rate is less than or approximates the maximum throughput, the intersection is considered to be unsaturated or saturated. Based on these, vehicle arrivals rates at approaches under three different conditions are set as Table.2, where the label of traffic flow is consistent with Fig.5. In order to simplify calculation, the right-turn volume is assumed to be 0 during simulation. Furthermore, according to the operation characteristics of traffic flow at intersection, vehicle arrivals at approaches should satisfy with an impulse function shown in Fig.7 and expressed as (11).

$$r(t) = \begin{cases} s & t_1 \le t \le t_2 \text{ or } t_3 \le t \le t_4 \\ 0 & \text{otherwise}, \end{cases} \tag{11}$$

where s is the saturation flow rate.

TABLE 1. Parameters of KH-CCSD algorithm.

parameters	description	value	unit
N	total number of krill individuals	20	—
ITE	maximum iteration number	100	—
$N^{\max}$	maximum induced speed	0.01	m/s
ω_n	inertia weight of the last motion induced	0.1	—
V_f	forging speed	0.02	m/s
ω_f	inertia weight of the last forging motion	0.1	—
$D^{\max}$	maximum diffusion speed	0.005	m/s
—	minimum green time	10	s
—	maximum green time	60	s
—	start-up lost time	0	s
I	yellow time	2	s
—	maximum throughput of intersection	3200	veh/h

TABLE 2. Vehicles arrival rates at approaches under different conditions.

traffic flow	1	2	3	4	5	6	7	8	9	10	11	12
unsaturation(veh/h)	—	350	250	—	300	200	—	450	300	—	400	250
saturation(veh/h)	—	430	340	—	420	300	—	530	370	—	480	330
oversaturation(veh/h)	—	500	400	—	490	390	—	580	430	—	530	380

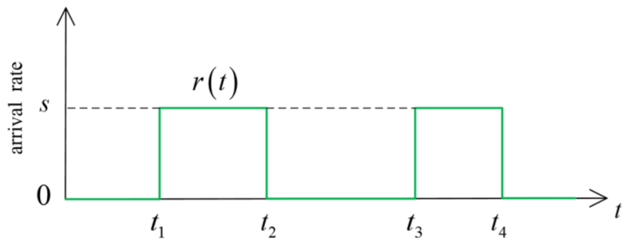

FIGURE 7. Vehicles arrival rate at approaches.

B. EVALUATION INDEX

To evaluate the proposed algorithm, the following indexes in VISSIM are selected, which reflect the travel delay, throughput and queuing of intersection.

(1) Total throughput during the simulation period TT and average throughput in unit time AT;

(2) total stop time of vehicles TS and average stop time per vehicle AS;

(3) total number of stops TN and average number of stops per vehicle AN;

(4) maximum queue length MQ and average queue length AQ of all lanes.

C. CONVERGENCE OF KH-CCSD

To investigate the influence of krill swarm initializations on KH-CCSD's convergence, three types of initializations are set under unsaturated, saturated and oversaturated conditions. The initialization of krill individual is as follows:

I: $\forall g_i \in G, g_i = 0$;

II: $\forall g_i \in G$, g_i is chosen randomly between 0 and $\arg_{g_i} g_i = h^* (S(t_i + g_i) \cap D(t_i + g_i))$;

III: $\forall g_i \in G, g_i = h^* (S(t_i + g_i) \cap D(t_i + g_i))$;

where I represents zero states, III denotes the maximum permitted states, and II is a random state between I and III. The experiments under initialization I, II, and III are named as KH-CCSD-I, KH-CCSD-II and KH-CCSD-III respectively. The results on convergence of KH-CCSD are shown in Fig.8-10, where results in Fig.8, Fig.9 and Fig.10 are under unsaturated, saturated and oversaturated conditions respectively. As shown in Fig.8, iteration times in KH-CCSD-I are around 30 when the curve become convergent, and yet in KH-CCSD-II and KH-CCSD-III the curve become convergent when iteration times are about 60. As a result, under unsaturated condition, the proposed method has best convergence by using initialization I. From Fig.9-10, it can be seen that the iteration times of KH-CCSD-I and KH-CCSD-III are around 30 when the curve become convergent, however, in KH-CCSD-II the curve become convergent when iteration times are about 60. Therefore, when the intersection is saturated and oversaturated, initialization I and III should be set in KH-CCSD.

D. COMPARED EXPERIMENTS AND RESULTS

To evaluate the effectiveness of KH-CCSD, it is compared with Webster method [37] and CABP [14] under unsaturated, saturated and oversaturated conditions by analyzing the spillover of exits and evaluation indexes. Webster method will fail when the intersection is oversaturated, so the experiments of Webster method are not carried out under oversaturated condition.

First, the simulation experiments of KH-CCSD, Webster method and CABP under the three conditions are carried out to investigate whether spillover will happen or not, and the results are shown in Table.3. According to Table.3,

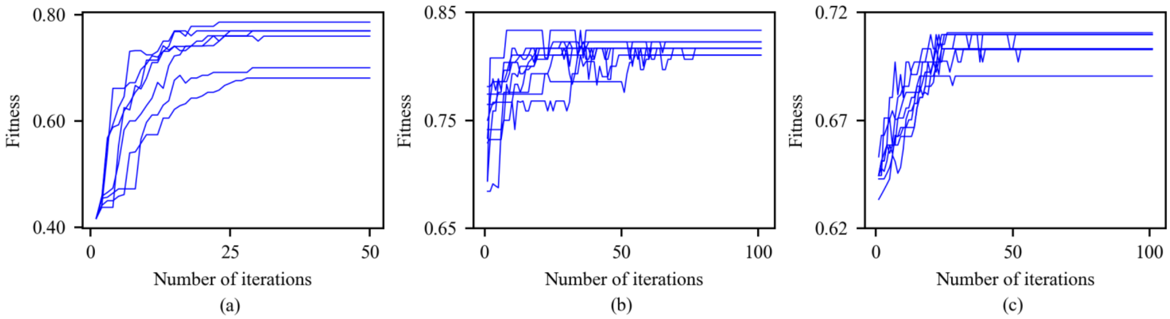

FIGURE 8. The convergence of KH-CCSD under unsaturated condition. (a) The convergence of KH-CCSD-I, (b) the convergence of KH-CCSD-II, and (c) the convergence of KH-CCSD-III.

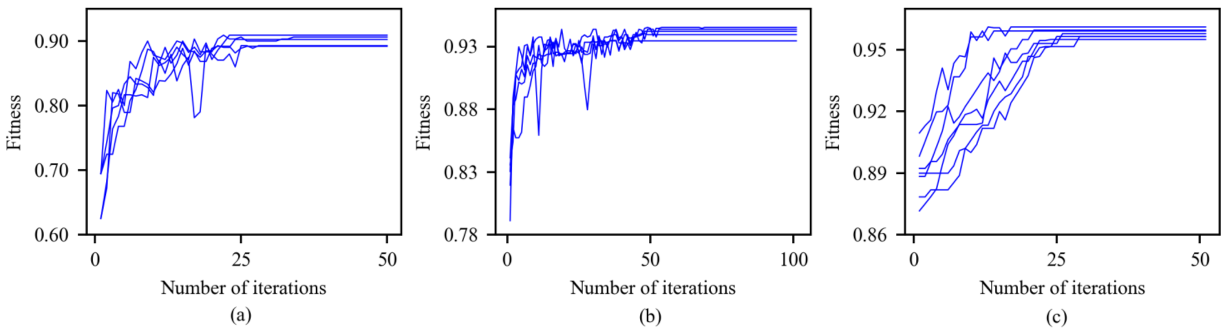

FIGURE 9. The convergence of KH-CCSD under saturated condition. (a) The convergence of KH-CCSD-I, (b) the convergence of KH-CCSD-II, and (c) the convergence of KH-CCSD-III.

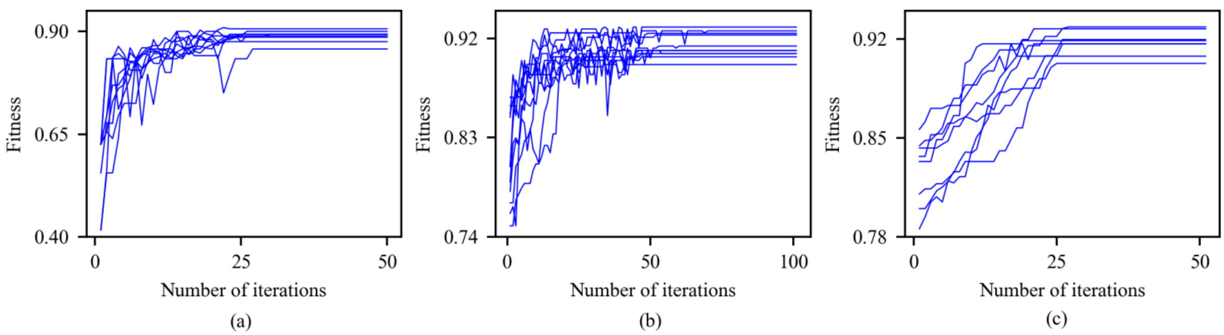

FIGURE 10. The convergence of KH-CCSD under oversaturated condition. (a) The convergence of KH-CCSD-I, (b) the convergence of KH-CCSD-II, and (c) the convergence of KH-CCSD-III.

TABLE 3. Spillover of exits under different conditions.

traffic condition	unsaturation	saturation	oversaturation
Webster	×	√	—
CABP	×	×	×
KH-CCSD	×	×	×

spillover only happened under saturated condition by using Webster method, and the simulation scene of spillover is given in Fig.11.

In addition, the compared experiments of KH-CCSD, Webster method and CABP under the three conditions are conducted to evaluate the performance of KH-CCSD by analyzing the throughput, stop time, the number of stops and queue length, and the results are given in Table.4-8 and Fig.12-14.

From Table.4, Table.7 and Fig.12 it can be seen that the throughput is similar to each other when the intersection is

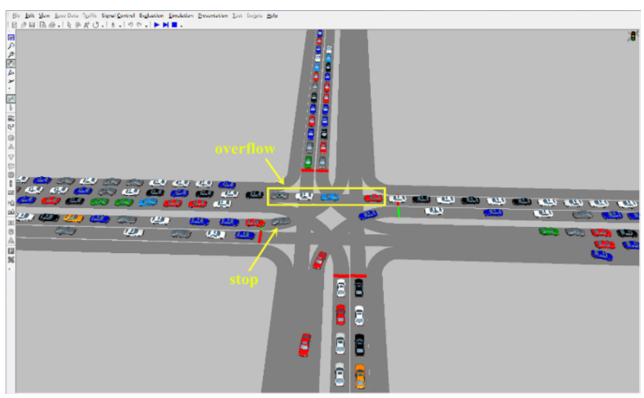

FIGURE 11. Vehicles overflow scene by Webster method.

unsaturated. However, under saturated and oversaturated conditions, the throughput in KH-CCSD is more than the other two methods. Besides, average throughput of KH-CCSD

TABLE 4. Total throughput and average throughput under different conditions.

traffic condition	unsaturation		saturation		oversaturation	
index	*TT* (veh)	*AT* (veh/h)	*TT* (veh)	*AT* (veh/h)	*TT* (veh)	*AT* (veh/h)
Webster	1219	2438	1310	2620	—	—
CABP	1214	2428	1393	2786	1414	2828
KH-CCSD	**1220**	**2440**	**1459**	**2918**	**1520**	**3040**

TABLE 5. Total stop time and average stop time under different conditions.

traffic condition	unsaturation		saturation		oversaturation	
index	*TS* (s)	*AS* (s/veh)	*TS* (s)	*AS* (s/veh)	*TS* (s)	*AS* (s/veh)
Webster	51038	40.8	229850	146.4	—	—
CABP	40970	32.7	149656	95.3	293692	161.9
KH-CCSD	**40190**	**32.1**	**92870**	**59.2**	**227842**	**125.6**

TABLE 6. Total number of stops and average number of stops under different conditions.

traffic condition	unsaturation		saturation		oversaturation	
index	*TN* (times)	*AN* (times/veh)	*TN* (times)	*AN* (times/veh)	*TN* (times)	*AN* (times/veh)
Webster	1533	1.22	2575	1.64	—	—
CABP	1856	1.48	4133	2.63	7670	4.23
KH-CCSD	**1453**	**1.16**	**2282**	**1.45**	**3188**	**1.76**

TABLE 7. Relative change of KH-CCSD in evaluation indexes compared with Webster and CABP.

traffic condition	unsaturation			saturation			oversaturation		
index	*AT*	*AS*	*AN*	*AT*	*AS*	*AN*	*AT*	*AS*	*AN*
KH-CCSD-Webster	0	-21.30%	-4.90%	11.40%	-59.60%	-11.60%	—	—	—
KH-CCSD-CABP	0.50%	-1.80%	-21.60%	4.70%	-37.90%	-44.90%	7%	-22.40%	-58.40%

TABLE 8. Maximum queue length and average queue length under different conditions.

traffic condition	unsaturation		saturation		oversaturation	
index	*MQ* (m)	*AQ* (m)	*MQ* (m)	*AQ* (m)	*MQ* (m)	*AQ* (m)
Webster	92.9	29.4	322	145.8	—	—
CABP	86.6	24.9	228.2	96.3	417.9	197.3
KH-CCSD	**85.1**	**24.4**	**169.9**	**60.8**	**325.9**	**146.3**

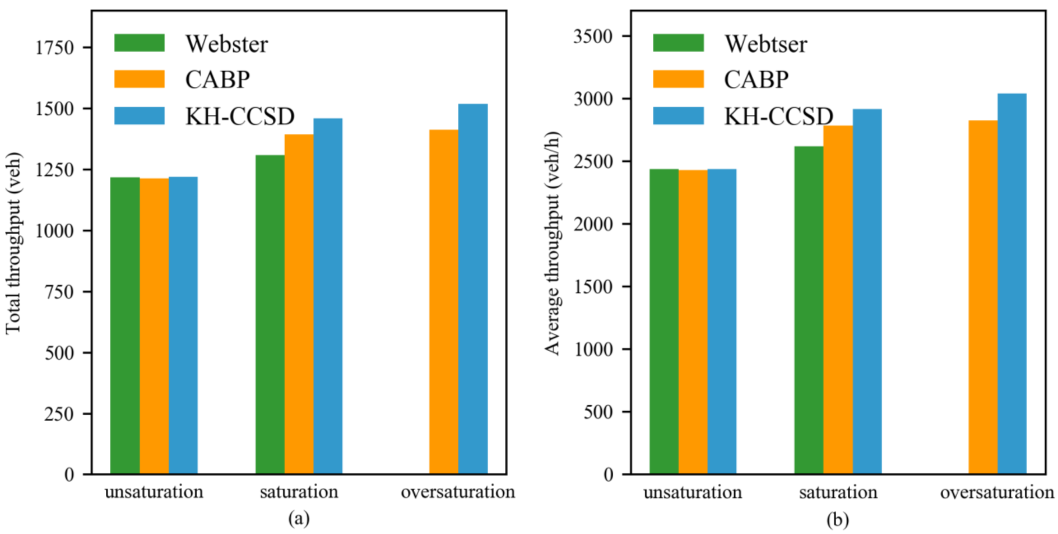

FIGURE 12. Comparison of throughput under different conditions. (a) Total throughput and (b) average throughput.

increases by 11.4% and 4.7% compared with Webster method and CABP under saturated condition, and 212 more vehicles in KH-CCSD passed through the intersection in an hour than that of CABP under oversaturated conditions.

The total stop time and average stop time are shown in Table.5 and Fig.13. Compared with Webster method and CABP, average stop time of KH-CCSD decreases by 21.3% and 1.8% under unsaturated condition. And the

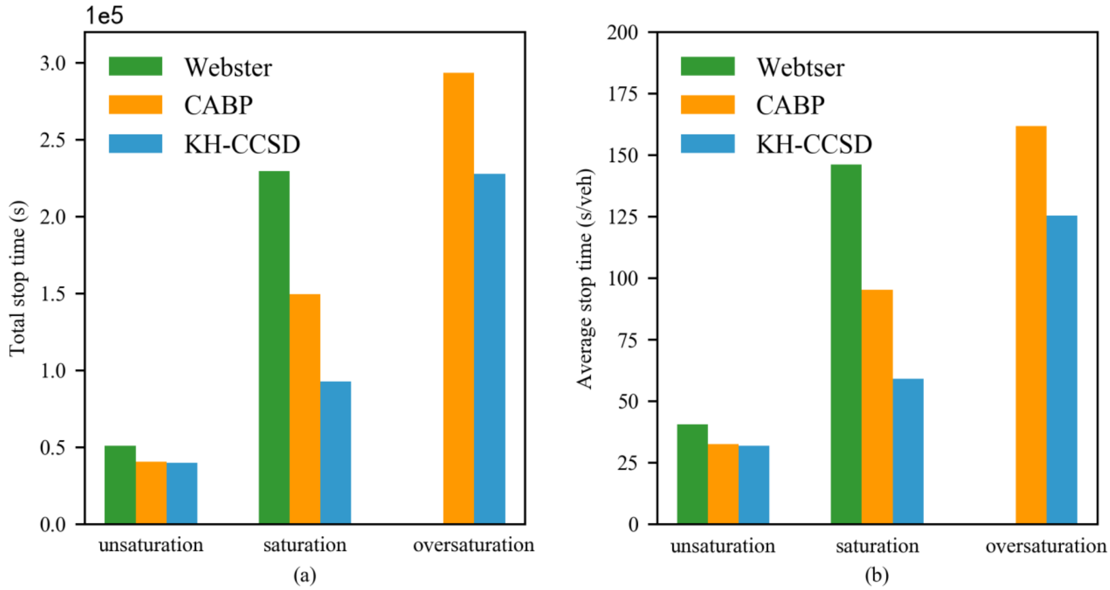

FIGURE 13. Comparison of stop time under different conditions. (a) Total stop time and (b) average stop time.

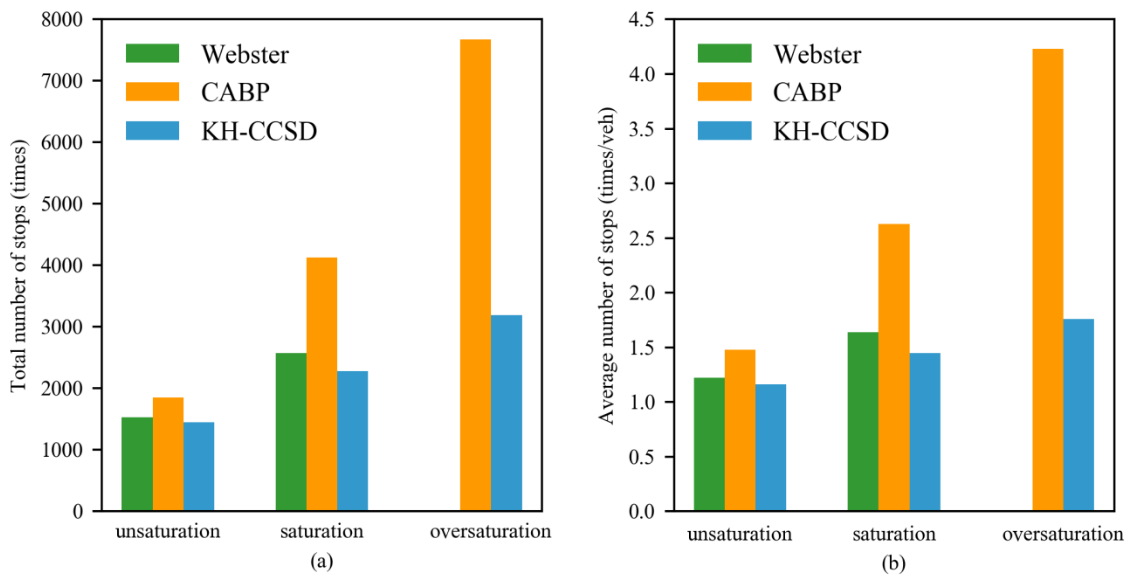

FIGURE 14. Comparison of the number of stops under different conditions. (a) Total number of stops and (b) average number of stops.

decrement is more than 55% and 35% under saturated condition. Especially, a vehicle will spend 36s less to pass the intersection by KH-CCSD rather than CABP when intersection is oversaturated.

Table.6 and Fig.14 provide the total number of stops and average number of stops for the three different methods.

Obviously, the number of stops is decreased by using KH-CCSD. To KH-CCSD, average number of stops decreases greatly compared with CABP, and the decrement is up to 21.6%, 44.9% and 58.4% under three conditions. Furthermore, there is also a reduction of 4.9% and 11.6% for KH-CCSD under unsaturated and saturated conditions compared with Webster method.

The maximum and average queue length of all lanes are shown in Table.8, and it can be seen that the maximum and average queue length of KH-CCSD are superior than those of Webster method and CABP, especially in saturated and oversaturated conditions. Under saturated condition, maximum queue length of KH-CCSD, comparing with that of Webster method and CABP, are reduced by 152 meters, 58 meters respectively, meanwhile, average queue length of KH-CCSD are reduced by 85 meters and 35.5 meters. Besides, under oversaturated conditions, the maximum and average queue lengths of KH-CCSD are decreased by 92 meters, 51 meters comparing with those of CABP.

From the above, KH-CCSD is superior to Webster method and CABP in throughput, stop time, the number of stops and queue length under unsaturated, saturated and oversaturated conditions. KH-CCSD can also prevent queue spillover, and satisfy the control requirements of intersection under unsaturated, saturated and oversaturated conditions.

VI. CONCLUSIONS

As a novel signal control method, CCSD could satisfy the control requirements under all traffic conditions and avoid the queue spillover at intersection. However, the optimization solution of CCSD cannot satisfy the real-time control requirement for its exhaustive search. Aiming at this problem, in this paper, the optimization problem is reconstructed by time-varying traffic supply and demand, and the optimization problem is reduced as a search optimization problem in a multi-dimensional space cooperatively constrained by traffic supplies and demands. As a superior optimization solution method, KH algorithm is introduced and employed to solve the optimization problem. To satisfy the search for krill swarm, the search space representation and fitness function of KH algorithm are constructed according to CCSD. Then the optimal signal timing plan is achieved by iterated search of krill swarm. Simulation experiments are carried out to evaluate the convergence and effectiveness of KH-CCSD under unsaturated, saturated and oversaturated conditions. And the experiments results show that KH-CCSD performs a fast converge and is superior to Webster method and CABP. As a result, KH-CCSD could satisfy the application of CCSD under all traffic conditions and avoid queue overflow.

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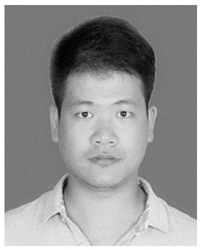

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