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A HARMONY SEARCH ALGORITHM APPROACH FOR OPTIMIZING TRAFFIC SIGNAL TIMINGS

ABSTRACT

In this study, a bi-level formulation is presented for solving the Equilibrium Network Design Problem (ENDP). The optimization of the signal timing has been carried out at the upper-level using the Harmony Search Algorithm (HSA), whilst the traffic assignment has been carried out through the Path Flow Estimator (PFE) at the lower level. The results of HSA have been first compared with those obtained using the Genetic Algorithm (GA) and the Hill Climbing on a two-junction network for a fixed set of link flows. Secondly, HSA with PFE has been applied to the medium-sized network to show the applicability of the proposed algorithm in solving ENDP. Additionally, in order to test the sensitivity of perceived travel time error, we have used HSA with PFE with various level of perceived travel time. The results showed that the proposed method is quite simple and efficient in solving ENDP.

KEY WORDS

harmony search algorithm, equilibrium network design problem, sensitivity parameter

1. INTRODUCTION

In urban road networks, traffic signals have been used to control vehicle movements in order to reduce congestion, improve safety, and enable specific strategies such as minimizing delays, prioritizing public transport and improving environmental pollution [1]. In a road system, the relationship between traffic managers and users is a typical asymmetric game, well-known as a sequential game [2]. Equilibrium Network Design Problem (ENDP) can be characterized by the so called bi-level structure. In the upper level, a transport planner designs the network. Road users respond to that design in the lower level. Bi-level problems are generally difficult to solve, because the solving of the upper level objective function involves solving the lower level problem for every feasible set of upper level decisions. Moreover, due to non-convexity of their feasible region, these problems are among the most attractive mathematical problems in the optimization field.

Through the years, a large variety of methods have been developed, and continuously improved, to optimize traffic signal timings, and to solve ENDP. First Webster [3], in his pioneering work, considered an isolated signalized junction. Afterwards, Robertson [4] developed the TRANSYT model, able to optimize a group of signalized junctions. Dealing with the dependence of the stochastic equilibrium link flows on signal settings for Area Traffic Control (ATC), the paper [5] found mutually consistent traffic signal settings and traffic assignment for a medium size road network. ENDP was solved by [6] using a direct search based on the Hooke-Jeeves method for a small test network. Heydecker and Khoo [7] proposed a constrained linear approximation to the equilibrium flows with respect to signal setting variables, and solved the bi-level problem as a constrained optimization problem.

Similarly, Cantarella et al. [8] proposed an iterative approach, in which traffic signal settings are performed in two successive steps: green timing at each junction, and signal co-ordination on the network. To solve the bi-level program for ENDP, paper [9] used derivatives both of equilibrium flows, and of the corresponding travel times. Heydecker [10] proposed a decomposition approach to optimize signal timings both at individual and at network level, based on the group-based variables.

Applications of different heuristic methods to solve the ATC problem have started to play an important role, especially during the last decade. Paper [11] explored a mixed search procedure to solve ATC problem confined to equilibrium network flows. Ceylan and Bell [12] proposed a Genetic Algorithm (GA) approach to solve traffic signal control and traffic assignment problem.

A joint optimization problem for solving the ATC was investigated by [13]. Ceylan [14] developed a GA with hill-climbing optimization routine and proposed a method for decreasing the search space to optimize signal timings for ATC. Chiou [15] used projected conjugate gradient method to solve the signalized road network problem with global convergence. Similarly, Chiou [16] proposed a new method to solve the ENDP while taking into account the route choice of users. Paper [17] solved the oversaturated network traffic signal coordination problem using the Ant Colony Optimization and GA approaches.

The optimization methods developed so far to solve the ENDP are either mathematically lengthy as for calculation, or based on heuristic approaches. Although proposed algorithms are capable to solve the ENDP for a road network, an efficient algorithm, capable to find global or near global optima of the upper level signal timing variables is still needed. For this purpose, in this paper we propose a bi-level method, in which the upper level problem deals with ATC problem, whilst the lower level problem deals with the traffic assignment. The Harmony Search Algorithm (HSA) is used to solve the upper-level optimization problem by calling the TRANSYT-7F [28], whilst the lower level problem is formulated based on the Stochastic User Equilibrium (SUE) assumption, and solved by using Path Flow Estimator (PFE) proposed by [18]. Implementing a new methodological approach for determining the Performance Index (PI) for a given road network was not the aim of this paper; therefore, a commercial package (TRANSYT-7F) has been used to determine the PI value with respect to the signal timings at the upper level.

This paper is organized as follows. In Section 2 notations are defined. Section 3 is about the formulation. Numerical application is carried out in Section 4. Sensitivity analysis on stochastic equilibrium networks using HSA and PFE is given in Section 5. The last section is about conclusions.

2. NOTATIONS

c – common cycle time;
c_{min} – minimum cycle time;
c_{max} – maximum cycle time;
d_a – delay on link a;
$\mathbf{h}$ – vector of path flows;
I – intergreen time between signal stages;
K – stop penalty factor;
$\boldsymbol{L}$ – set of links, $a \in \boldsymbol{L}$;
$\boldsymbol{M}$ – set of signal stages, $m \in \boldsymbol{M}$;
$\boldsymbol{N}$ – set of nodes, $n \in \boldsymbol{N}$;
S_a – stops on link a per second;
$\mathbf{t}$ – vector of origin destination flows;
$\mathbf{q}$ – vector of link flows;
$\boldsymbol{q}^*(\psi)$ – vector of equilibrium link flows subject to signal parameters;
$\boldsymbol{W}$ – set of origin-destination pairs;
w_{d_a} – weighting factor for delay on link a;
w_{s_a} – weighting factor for stops on link a;
x_a – degree of saturation on link a;
θ – vector of offset variables;
φ – vector of duration of green times;
φ_{min} – minimum duration of stage green timings;
φ_{max} – maximum duration of stage green timings;
Ψ – vector of signal timings;
Ψ_{min} – lower bound vector of signal timings;
Ψ_{max} – upper bound vector of signal timings;
Ω – feasible set of signal setting variables;
δ – link-path incidence matrix;
Λ – OD-path incidence matrix.

3. FORMULATION

The optimization of signal timings $\psi = (c, \theta, \varphi)$ on a road network can be defined as a bi-level structure. The objective function is to minimize the PI with respect to equilibrium link flows $\boldsymbol{q}^*(\psi)$ subject to signal timings $\psi = (c, \theta, \varphi)$. From a mathematical point of view, the problem is defined as:

$$\underset{\psi \in \Omega}{\text{Minimise}}\ \text{PI}(\psi, \mathbf{q}^*(\psi)) = \sum_{a \in \mathbf{L}} (w_{d_a} d_a + K w_{s_a} S_a) \tag{1}$$

subject to

$$\psi(c, \theta, \varphi) \in \Omega; \begin{cases} c_{min} \le c \le c_{max} \\ 0 \le \theta \le c \\ \varphi_{min} \le \varphi \le \varphi_{max} \\ \sum_{i=1}^{m} (\varphi_i + I_i) = c \quad \forall m \in \boldsymbol{M}, \forall n \in \boldsymbol{N} \end{cases}$$

where $\boldsymbol{q}^*(\psi)$ is implicitly defined by

$$\underset{q}{\text{Minimise}}\ Z(\psi, \mathbf{q}) \tag{2}$$

subject to

$$\mathbf{t} = \Lambda\mathbf{h},\ q = \delta\mathbf{h},\ \mathbf{h} \geq 0$$

The solution to the signal optimization problem involves the following parameters: cycle time, offsets and green timings. Each decision vector ψ can take values from the domain $\Omega = [\psi_{\min}, \psi_{\max}] \subseteq R$. One of the advantages of HSA to solve the upper level problem is that we do not need to code the decision variables in order to optimize the objective function. The numbers from the range $[\psi_{\min}, \psi_{\max}]$ are used to optimize the objective function as follows.

$$\begin{array}{llll} \text{Range} & [c_{\min}, c_{\max}] & [o, c] & [\varphi_{\min}, \varphi_{\max}] \\ & \downarrow & \downarrow & \downarrow \\ \text{Decision variables} & |c| & |\theta_1, \theta_2, \ldots, \theta_n| & |\varphi_1, \varphi_2, \ldots, \varphi_n| \end{array}$$

In order to provide the green timings constraint, the following relation can be used in a road network [26]:

$$\varphi_i = \varphi_{\min,i} + \frac{\varphi_i}{\sum_{k=1}^{m} \varphi_i}\left(c - \sum_{k=1}^{m} l_k - \sum_{k=1}^{m} \varphi_{\min,k}\right) \quad i = 1, 2, \ldots, m \tag{3}$$

where φ_i is the green time for stage i and c is the common cycle time of the network. The advantage of such a distribution process is that it ensures the sum of the green timings of each stage will be equal to the common cycle time.

3.1 HSPFE for optimization of traffic signal timings

HSA is a meta-heuristic method, based on the musical process of searching for a perfect state of harmony, such as jazz improvisation [19]. In this improvisation process, the members of a music group try to find the best harmony as determined by an aesthetic standard, just as the optimization algorithm tries to find the global optimum as determined by the objective function. The notes and the pitches getting played by the individual instruments determine the aesthetic quality, like the objective function value determined by the values assigned to design variables. The harmony quality is enhanced practice after practice, just as the solution quality is enhanced iteration by iteration. In HSA, four parameters are used to control the solution procedure: Harmony Memory Size (HMS), which represents the number of solution vectors in the harmony memory; Harmony Memory Considering Rate (HMCR) that is the probability of assigning the values to the variables from harmony memory; Pitch Adjusting Rate (PAR) that sets the rate of adjustment for the pitch chosen from the Harmony Memory (HM); and the number of improvisations (NI) that represents the Number of Iterations to be used during the solution process. NI can also be assumed as the termination criterion [20]. HM is a memory location where all the solution vectors and corresponding objective function values are stored. The function values are used to evaluate the quality of solution vectors. HSA also considers several solution vectors simultaneously, in a manner similar to GA. However, the major difference between the two heuristic algorithms is that HSA generates a new vector from all the existing vectors, whereas GA produces a new vector from only two of the existing vectors.

HSA-based algorithms have been applied to a wide set of different engineering problems, ranging from the minimum cost design of steel frames [21], to the identification of unknown groundwater pollution sources [22], to the optimum design of cellular beams, along with particle swarm optimization methods [23]. However, applications in the transportation area of HSA-based algorithms are still limited [20, 24]. Thus, HSPFE, which is a combination of HSA and PFE, has been developed to solve ENDP and its solution steps are given as follows:

Step 0: Set the user-specified HSA parameters.

Step 1: Generate HM of signal timings ψ by giving the minimum $\psi_{\min}$ and maximum $\psi_{\max}$ bounds as integer seconds. Green timings are distributed using Eq. (3) to all signal stages in order to provide the green timing constraints in a given road network.

Step 2: A new harmony vector is generated based on memory consideration, pitch adjustment, and random selection. In the memory consideration, the value of the first signal timing for the new vector is selected from any value in the specified HM range generated in Step 1. Values of other signal timings are selected in the same manner. The HMCR parameter varies between 0 and 1 and represents the rate of choosing one value from HM whereas (1-HMCR) is the rate of randomly selecting a value from the possible range. The next step under the improvisation process is to check whether the pitch adjustment is necessary or not. Pitch adjustment probability is evaluated with parameter of PAR, which represents the pitch adjusting and varies between 0 and 1 [20].

The HMCR and PAR parameters introduced in HSA help the algorithm to find globally and locally improved solutions. Geem [25] has recommended parameter values ranging between 0.70 and 0.95 for HMCR, 0.20 and 0.50 for PAR, and 10 and 50 for HMS to produce good performance of HSA. Hence, in this study HMCR and PAR have been selected as 0.70 and 0.45, respectively. The effect of HSA parameters on the signal timing optimization is not taken into account. This is out of the scope of this study.

Step 3: Solve the lower level problem through PFE, using populated signal timings in HM. This procedure gives SUE link flows for each link a in L.

In Step 3, the link travel time (u) is considered as the sum of free-flow travel time and average delay at the stop line at a signal-controlled junction by simplifying the offset expressions for PFE, where the corresponding expressions can be obtained in [26].

Step 4: Find the values of PI for resulting signal timings in Steps 1-2, and the corresponding equilibrium link flows resulting in Step 3 by running TRANSYT-7F.

Step 5: All of the PI values in HM are set in descending order, from the best to the worst. New harmony vector is compared with the vector giving the worst PI value in this Step. If the new harmony vector gives a better PI value than the worst one, it is included in HM and the worst one is excluded from HM.

Step 6: Check the termination criterion. If the difference between the average of PI values in HM and best PI value is less than the predetermined value, the algorithm is terminated. Else go to Step 7.

Step 7: Terminate the algorithm if the maximum number of function evaluations is reached. Else go to Step 2.

4. NUMERICAL APPLICATION

The application of HSPFE for finding optimal signal parameters has been tested on Allsop and Charlesworth's network, chosen according to [26], where the ATC is carried out at the upper-level based on the HSA, and the traffic assignment is performed at the lower-level through PFE. The optimization procedure in TRANSYT-7F is based on GA and Hill-Climbing Algorithm (HCA). The HCA searches for the best signal timings by a trial and error method. It is an iterative, gradient search technique that requires numerous simulation runs. TRANSYT-7F also offers a GA search technique, which performs a multidirectional search by maintaining a population of potential solutions and encourages information exchange between these directions. Both GA and HCA methods have advantages and disadvantages in terms of their ability to find a global solution and Central Processing Unit (CPU) time. In order to show the applicability of HSA for solving the upper level problem of ENDP, the performances of HSA, GA and HCA have been compared using the TRANSYT-7F package with a fixed set of link flows. We have called HSTRANS, GATRANS and HCTRANS, respectively, the combination of HSA, GA and HCA with TRANSYT-7F.

The performance comparison has been conducted by solving a two-junction network. The basic layout of the two-junction network for use in TRANSYT-7F is given in *Figure 1*.

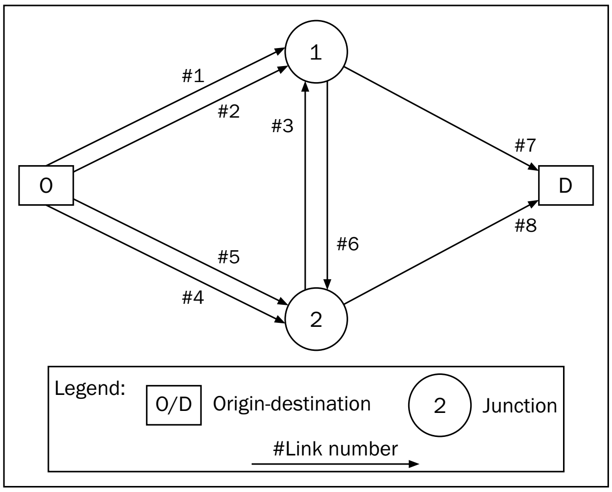

Figure 1 - Two-junction network

In order to compare the HSTRANS with the GATRANS and the HCTRANS optimization routines, the test road network is considered containing two signal-controlled junctions, one O-D pair w in W, and eight links. The fixed values of the input data for the network can be obtained in [26]. The signal timing constraints are set as follows:

$c_{min}, c_{max} = 36, 90$ s	Common network cycle time;
$\theta_{min}, \theta_{max} = 0, 90$ s	Offset;
$\varphi_{min} = 5$ s	Minimum green time;
$I = 5$ s	Intergreen time for all stages.

HSTRANS is performed with the user-specified parameters such as HMS=20, HMCR=0.70 and PAR=0.45. The crossover and mutation probabilities are set as 0.30 and 0.01, which are default GA parameters used in TRANSYT-7F. In addition, the maximum number of generations and population size for GA are selected as 100 and 20, respectively. HSTRANS has been executed in MATLAB programming, by internally calling TRANSYT-7F and performed on PC with Intel Core2 2.00 GHz, RAM 2 GB. Each function evaluation took less than 1.5 seconds of CPU. The total computation time for 2,000 function evaluations and a harmony memory size of 20 for the complete run of HSTRANS took about 43 minutes. The termination conditions were set as: difference between the average of PI values and best PI value in HM less than 5%, or reaching of the maximal number of function evaluations. The HSTRANS solution for the fixed set of link flows is given in *Figure 2*. As can be seen in the Figure, the HSTRANS application shows steady convergence towards the optimum or near optimum. The minimum PI is achieved at the 1,419th function evaluation. The common network cycle time obtained 76 seconds and the PI found is 8.1624. HCTRANS and GATRANS are also carried out for the same fixed set of link flows. The resulting common network cycle times and the corresponding duration of stages are given in *Table 1*.

Table 1 - The results of compared algorithms for the fixed set of link flows

Model	PI	Cycle time c (sec)	Junction number (n)	Stage 1 $\varphi_{n,1} + I_{n,1}$	Stage 2 $\varphi_{n,2} + I_{n,2}$	θ_n
HSTRANS	8.1624	76	1	55	21	0
			2	66	10	65
HCTRANS	8.1877	78	1	55	23	0
			2	68	10	10
GATRANS	8.1779	79	1	58	21	0
			2	69	10	6

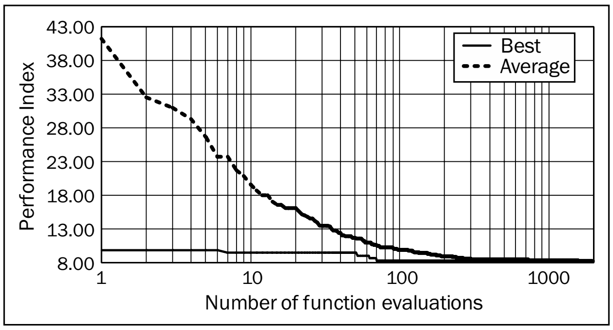

Figure 2 - The convergence of HSA for the two-junction network

The performance of GATRANS is better than HCTRANS because the resulting minimum PI for GATRANS is 8.1779 and the resulting common cycle time is 79 seconds. With HCTRANS, the minimum PI resulted in 8.1877 and the common network cycle time is 78 seconds. According to the results, HSTRANS gives slightly better results than HCTRANS and GATRANS in terms of PI value. On the other hand, the improvement of PI using HSTRANS for small network encourages the application of HSPFE to the medium-sized network.

4.1 HSPFE for Allsop and Charlesworth's network

Allsop and Charlesworth's network includes 20 O-D pairs and 21 signal setting variables at six signal-controlled junctions. Fixed data used for test network and travel demands for each O-D can be obtained in [12]. Layout of the network is given in *Figure 3*. HSPFE is performed with the following user-specified parameters: HMS=40, HMCR=0.70, PAR=0.45 and the maximal number of function evaluations (t) is 5,000. The signal timing constraints are given as follows:

$c_{min}, c_{max} = 36, 140$ s Common network cycle time;

$\theta_{min}, \theta_{max} = 0, 140$ s Offset;

$\varphi_{min} = 5$ s Minimum green time;

$I = 5$ s Intergreen time for all stages.

Although the bi-level solution of signal optimization problem is non-convex and only a local optimum is expected to be obtained, HSPFE may be able to avoid being trapped in a bad local optimum. In fact, HSA uses a stochastic random search based on the parameters HMCR and PAR, which effectively guide a global search rather than a gradient search, so that derivative information is unnecessary. Moreover, the proposed method is not dependent on the initial values of the signal setting variables, and imposes fewer mathematical requirements, in comparison to gradient-based mathematical optimization algorithms and to some other heuristic methods. In addition, HSA generates a new vector after having considered all existing vectors based on HMCR and PAR, rather than considering only two (parents) like in GAs. According to paper [27], these features increase the flexibility of HSA and produce better solutions.

We have applied HSPFE to the Allsop and Charlesworth's network for a fixed number of function evaluations (improvisations), namely 5,000, given the harmony memory size of 40. When the average and best PI values have converged to approximately the same

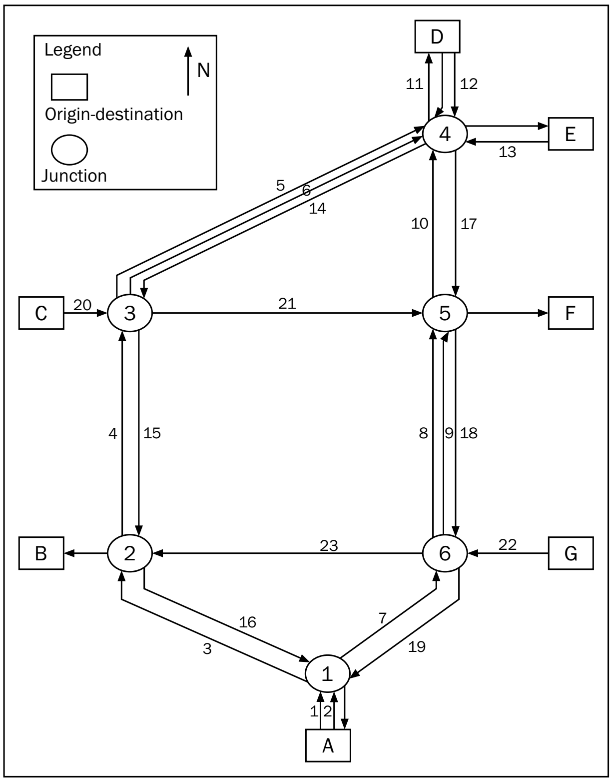

Figure 3 - Allsop and Charlesworth's network

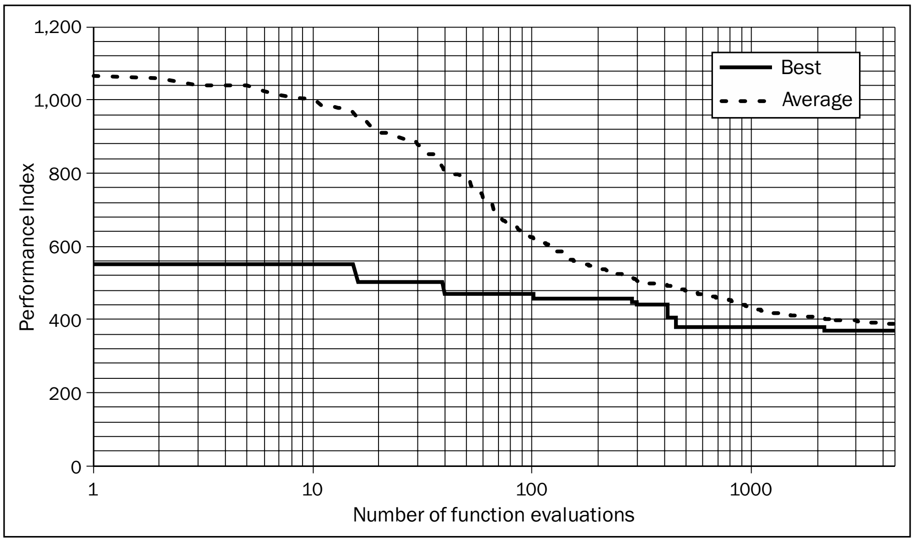

Figure 4 - Application of HSPFE to the Allsop and Charlesworth's network

value, we have assumed that HSPFE has found the optimum or near-optimum solution. The convergence of HSPFE has been achieved at the 4,497th function evaluation. The best resulting PI value was 368.60. The total computation effort for complete run of HSPFE resulted in 4.86 hours. The convergence of the HSPFE model can be seen in *Figure 4*. HSPFE, initially structured with randomly generated solution vectors, has calculated PI of each harmony vector in HM.

In the improvisation step, a new harmony vector is generated based on the rules such as memory consideration, pitch adjustment, and random selection. In memory consideration, the value of the first decision variable for the new vector is selected from any value in the specified HM range. The values of other decision variables are selected in the same manner. The next step under the improvisation process is to check whether the pitch adjustment is necessary or not. Pitch adjustment probability is evaluated with the PAR parameter, and varies between 0 and 1. The pitch adjusting process is performed only after a value has been chosen from HM. The value (1-PAR) sets the rate of doing nothing. After a new harmony vector is generated, the equilibrium link flows are obtained through PFE, and the PI values in HM are determined by means of the TRANSYT-7F package, using the set of generated signal timings and corresponding equilibrium link flows. Then, all of the PI values in HM are set in descending order, from the best to the worst, and a new harmony vector is compared with the vector giving the worst PI value. If the new harmony vector gives a better PI value than the worst one, the new harmony vector is included into HM, and the existing worst harmony is excluded from HM. When the difference between average and best PI values is less than 5%, HSPFE is terminated. Otherwise, a new harmony vector is generated in order to obtain better PI value, provided that the maximum number of function evaluations has not been reached.

In *Figure 4* there are no improvements on the best PI value after the first few function evaluations. Then the HSPFE starts to improve the PI values. The convergence of the HSPFE is achieved after the 4,497th function evaluation. The model initially started with a random generated harmony memory and picked up the best PI value within the harmony memory, which was about 550. HSPFE easily located the best values of PI after a couple of number of function evaluations, starting with harmony memory size of 40. A harmony memory size of 40 is usually sufficient to avoid being trapped in bad local optima when the number of decision variables of the given signal optimization problem

Table 2 - Equilibrium link flows and values of degree of saturation derived from HSPFE

q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8	q_9	q_{10}	q_{11}	q_{12}
720	460	720	594	638	175	460	477	109	477	500	250
x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}
0.39	0.48	0.39	0.45	0.62	0.32	0.82	0.77	0.76	0.72	0.90	0.24

q_{13}	q_{14}	q_{15}	q_{16}	q_{17}	q_{18}	q_{19}	q_{20}	q_{21}	q_{22}	q_{23}
450	791	791	663	409	349	627	1290	1071	1250	846
x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}	x_{20}	x_{21}	x_{22}	x_{23}
0.70	0.60	0.53	0.72	0.95	0.66	0.70	0.91	0.62	0.57	0.77

Table 3 - Signal timings derived from HSPFE

PI	Cycle time c (sec)	Junction Number (n)	Stage 1 $\varphi_{n,1}+I_{n,1}$	Stage 2 $\varphi_{n,2}+I_{n,2}$	Stage 3 $\varphi_{n,3}+I_{n,3}$	θ_n
368.60	119	1	43	76	-	0
		2	73	46	-	74
		3	65	54	-	46
		4	38	41	40	44
		5	15	35	69	40
		6	42	77	-	95

is considered. *Table 2* shows the final values of equilibrium link flows, and their corresponding degree of saturation resulting from HSPFE for the Allsop and Charlesworth's network. The final values of degree of saturation indicate that none of the links are oversaturated and the network is uncongested. *Table 3* shows the signal timings and the final value of PI. The common network cycle time resulting from the HSPFE application is 119 seconds, and the duration of stages in the signalized junctions are also presented in *Table 3*.

5. SENSITIVITY ANALYSIS ON STOCHASTIC EQUILIBRIUM NETWORKS USING HSPFE

In this section, the sensitivity of the perceived travel time error and its corresponding effects to the optimal signal timings are investigated using HSPFE. It is well known that any change in the sensitivity parameter will affect the drivers route choice behaviours, leading to a different PI and different signal timings in a given road network. When the sensitivity parameter is lower, the error on perceived travel time is bigger. As the level of information provided to the drivers decreases, their perception of travel time error in a road network increases. Drivers will perceive travel cost differently with the increasing level of information and they try to avoid the longer paths. As the perception parameter, α, becomes smaller, the perception error of travel times increase. On the other hand, α becomes bigger as the error in the perception of travel times becomes smaller, and the SUE assignment approaches to the UE assignment, where drivers have perfect information on travel times in the network. We have investigated through HSPFE the effect on system performance of any change in the perception of travel time. After the application of HSPFE, it was found that for values of α up to 1, the PI values remain high, and decrease rapidly for bigger values of α, as shown in *Figure 5*. This result is reasonable: in fact, the higher the value of α, the more deterministic the traffic assignment.

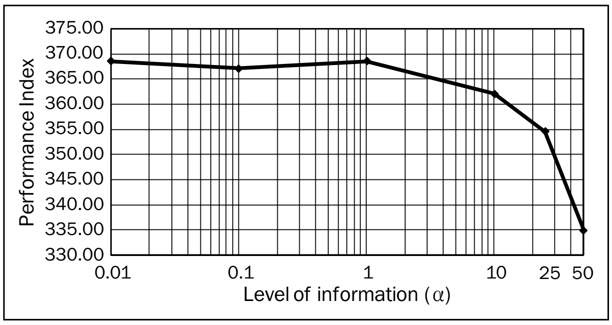

Figure 5 - Variation of PI for different α values

Table 4 - Final values of equilibrium link flows from HSPFE for different values of α

α	q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8	q_9	q_{10}	q_{11}	q_{12}
0.01	715	465	715	589	635	175	465	480	110	480	500	250
0.1	715	465	715	590	635	175	465	480	110	480	500	250
1.0	720	460	720	594	638	175	460	477	109	477	500	250
10.0	744	436	744	609	652	173	436	465	106	465	404	346
25.0	826	354	826	681	710	172	354	408	91	408	501	249
50.0	832	348	832	651	697	164	348	430	99	430	389	361

α	q_{13}	q_{14}	q_{15}	q_{16}	q_{17}	q_{18}	q_{19}	q_{20}	q_{21}	q_{22}	q_{23}
0.01	450	790	790	664	410	350	626	1290	1070	1250	850
0.1	450	790	790	664	410	350	626	1290	1070	1250	849
1.0	450	791	791	663	409	349	627	1290	1071	1250	846
10.0	450	711	713	673	489	427	617	1290	1072	1250	925
25.0	450	809	818	618	391	322	672	1290	1080	1250	755
50.0	450	696	709	481	504	431	809	1290	1068	1250	691

Table 5 - Final values of degree of saturation for different values of α

α	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}
0.01	0.39	0.49	0.39	0.48	0.64	0.35	0.76	0.78	0.82	0.69	0.89	0.23
0.1	0.39	0.52	0.38	0.52	0.62	0.35	0.78	0.68	0.85	0.72	0.84	0.23
1.0	0.39	0.48	0.39	0.45	0.62	0.32	0.82	0.77	0.76	0.72	0.90	0.24
10.0	0.41	0.51	0.49	0.53	0.70	0.34	0.79	0.64	0.61	0.60	0.81	0.32
250	0.45	0.36	0.43	0.54	0.66	0.34	0.75	0.65	0.68	0.69	0.76	0.23
50.0	0.32	0.40	0.56	0.69	0.27	0.61	0.55	0.60	0.63	0.85	0.37	0.32

α	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}	x_{20}	x_{21}	x_{22}	x_{23}
0.01	0.75	0.64	0.53	0.71	0.95	0.60	0.71	0.88	0.62	0.61	0.78
0.1	0.75	0.69	0.51	0.64	0.79	0.62	0.75	0.82	0.68	0.59	0.82
1.0	0.70	0.60	0.53	0.72	0.95	0.66	0.70	0.91	0.62	0.57	0.77
10.0	0.75	0.62	0.57	0.60	0.98	0.82	0.78	0.83	0.70	0.57	0.66
25.0	0.76	0.65	0.52	0.70	0.88	0.73	0.74	0.88	0.64	0.53	0.75
50.0	0.62	0.60	0.42	0.75	0.91	0.80	0.78	0.84	0.75	0.59	0.81

Table 6 – Signal timings for various values of α (second)

α	Junction 1			Junction 2			Junction 3		
	Stage 1 $\varphi_{n,1}+I_{n,1}$	Stage 2 $\varphi_{n,2}+I_{n,2}$	θ_1	Stage 1 $\varphi_{n,1}+I_{n,1}$	Stage 2 $\varphi_{n,2}+I_{n,2}$	θ_2	Stage 1 $\varphi_{n,1}+I_{n,1}$	Stage 2 $\varphi_{n,2}+I_{n,2}$	θ_3
0.01	42	72	0	70	44	72	65	49	114
0.1	47	71	0	75	43	85	71	47	98
1	43	76	0	73	46	74	65	54	46
10	50	67	0	61	56	1	70	47	21
25	40	75	0	74	41	47	65	50	27
50	30	83	0	78	35	88	67	46	39

α	Junction 4				Junction 5				Junction 6		
	Stage 1 $\varphi_{n,1}+I_{n,1}$	Stage 2 $\varphi_{n,2}+I_{n,2}$	Stage 3 $\varphi_{n,3}+I_{n,3}$	θ_4	Stage 1 $\varphi_{n,1}+I_{n,1}$	Stage 2 $\varphi_{n,2}+I_{n,2}$	Stage 3 $\varphi_{n,3}+I_{n,3}$	θ_5	Stage 1 $\varphi_{n,1}+I_{n,1}$	Stage 2 $\varphi_{n,2}+I_{n,2}$	θ_6
0.01	37	41	36	20	14	34	66	106	44	70	68
0.1	40	41	37	91	14	41	63	38	44	74	58
1	38	41	40	44	15	35	69	40	42	77	95
10	34	46	37	106	17	39	61	62	41	76	45
25	43	36	36	18	14	35	66	101	35	80	69
50	31	40	42	105	16	42	55	3	41	72	70

In Tables 4 and 5, the final values of equilibrium link flows and the corresponding final values of degree of saturation are given for various α. As can be seen from *Table 4*, the equilibrium link flows do not significantly vary when α varies between 0.01 and 1.0. Since the SUE approaches the UE, there is a significant change in the link flows when α value is higher than the value of 1.0.

The signal timings derived from HSPFE for different values α are given in *Table 6*. As can be seen from this table, α value affects signal timings on a signalized road network under SUE link flows. Therefore, the choice of α value according to the driver's behaviours on a signalized network is considerably substantial in order to obtain signal timings which can be provided by the minimum PI value.

6. CONCLUSION

The problem of combined traffic signal control and traffic assignment has been addressed in this paper. HSPFE for the bi-level solution of ENDP has been described and implemented to the Allsop and Charlesworth's network. Before that application, HSA has been compared with the GA and HCA optimization routines on the two-junction network for fixed set of link flows, in order to show the HSA's applicability in solving the upper level problem of ENDP. It was found that the performance of HSA was better than GA and HCA in terms of the PI value. It is emphasized that the results are dependent on the used parameters on three optimization methods, although the parameters were chosen as suitable as possible to make a more realistic comparison.

Afterwards, HSPFE has been applied to the Allsop and Charlesworth's test network to demonstrate the effectiveness of the proposed algorithm. The resulting equilibrium link flows and their corresponding degree of saturation are presented. The final values of degree of saturation indicate that none of the links are oversaturated, and the network is uncongested. Finally, the sensitivity of the perceived travel time error and its corresponding effects on the optimal signal timings are investigated using HSPFE. It was found that the signal timings derived from the proposed algorithm varied for different α values. Therefore, to solve the signal optimization problem under stochastic equilibrium link flows, an appropriate choice of parameter α is crucial.

The effect of HSA parameters on ENDP is not taken into account, since it was out of the scope of this study. Future work should deal with the effects of HSA parameters in solving ENDP. Furthermore, the analysis of the applicability of HSPFE for various real networks is needed, for better evaluation of the robustness and effectiveness of the proposed algorithm.

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ÖZET

ARMONİ ARAŞTIRMASI TEKNİĞİ İLE TRAFİK SİNYAL SÜRELERİNİN OPTİMİZASYONU

Bu çalışmada Denge Ulaşım Ağ Tasarım (DUAT) probleminin çözümü için iki seviyeli programlama yaklaşımı önerilmiş ve sinyal sürelerinin optimizasyonu üst seviyede Armoni Araştırması Tekniği (AAT) ile gerçekleştirilmiştir. Alt seviyede ise trafik atama problemi Rota Akım Tahmin (RAT) algoritması kullanılarak çözülmüştür. AAT algoritması ile elde edilen sonuçlar, sabit bağ akımları altında iki kavşaktan oluşan bir ulaşım ağında Genetik Algoritma (GA) ve Tepe Tırmanma (TT) metotları ile elde edilen sonuçlarla karşılaştırılmıştır. DUAT probleminin çözümünde AAT metodunun performansının test edilmesi amacıyla orta ölçekli bir ulaşım ağında uygulama yapılmıştır. Ayrıca algılanan seyahat süresinin duyarlılığının test edilmesi için analizler yapılmıştır. Sonuçlar önerilen metodun DUAT probleminin çözümünde oldukça etkili olduğunu göstermiştir.

ANAHTAR KELİMELER

armoni araştırması tekniği, denge ağ tasarım problemi, duyarlılık parametresi

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