SIGNAL OPTIMIZATION AND DYNAMIC USER EQUILIBRIUM TRAFFIC ASSIGNMENT IN CONGESTED URBAN ROAD NETWORK

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Abstract

This paper presents the joint optimization of signal setting parameters and dynamic user equilibrium (DUE) traffic assignment for the congested urban road network. The simulation-based approach is employed to obtain the DUE condition for the case of multiple-origin multiple-destination traffic flows. The dynamic traffic assignment simulation program (DTASP), developed in C language is used to assign the traffic dynamically on the road network, whereas method of successive averages (MSA) is modified and used to arrive at the user equilibrium condition. The artificial intelligence technique of genetic algorithms (GAs) is applied to obtain the optimal signal setting parameters and path flow distribution factor for DUE condition. The methodology developed in such a way that joint optimization of signal setting parameters with DUE is obtained. The proposed method is applied to example network of 14 nodes and 19 links with 6 Origin-Destination pairs and 3 signalized intersections, for the assumed demand flow. The traffic condition for the optimized signal setting parameters is considerably improved compared to the tentatively fixed signal settings. The computation time is considerably reduced for the joint optimization approach compared to the exhaustive search method.

Keywords: Signal optimization; Equilibrium; Traffic assignment; Simulation; Network;
Genetic algorithms
Topic Area: C3 Traffic Control

1. Introduction

The performance of a traffic network can be influenced through several types of actions or decision variables. Some of these pertain to changing the load pattern on the network, through demand management actions, including attempts to route vehicles optimally through the network; others pertain to how traffic flow is controlled through signal control (supply management). Conventional methods for traffic signal optimization assume fixed traffic flows; whereas the traffic assignment methods assume fixed signal settings. This separation of traffic control from assignment may lead to inconsistency between traffic flows and signal settings because they are in general inter-dependent. The inter-dependence tends to be more serious in congested networks. The inconsistency may be eliminated by combining signal optimization with an equilibrium assignment. The combined signal optimization and user equilibrium (UE) traffic assignment problem is one in which a traffic engineer tries to optimize the performance of signals while road users choose their routes in a UE manner (Maher and Zhang, 1999).

Some of the most important theoretical contributions to the problem of signal control and UE static assignment are made by Smith (1979, 1981), who derived conditions that guarantee the existence of an equilibrium as well as conditions for the uniqueness and stability of the traffic equilibrium when there is interaction between signal setting and users' route choice decisions. Allsop (1974) has proposed an iterative solution procedure for the UE static assignment problem in a pretimed signal-controlled network. Charlesworth (1977) obtained mutually consistent traffic assignment and signal settings through an iterative procedure in which the TRANSYT software is used to optimize the signal settings. In dynamic traffic assignment (DTA) Ghali and Smith (1993) have implemented an iterative procedure using CONTRAM and showed the convergence pattern for it. Gartner and Stamatiadis (1997) have presented a general conceptual framework for the implementation of a combined solution for DTA and signal control, but they have not reported implementation of a specific algorithmic procedure. Abdelfatah and Mahmassani (1998) have presented a formulation and solution algorithm for the combined system optimal DTA and signal control. Abdelghany et al. (1999) have introduced and illustrated the path-based signal coordination as an example of integrating signal control with network traffic assignment using the real-time DTA.

Signal optimization and DUE condition can be carried out as a joint optimization problem or as a bi-level programming problem. In the joint optimization problem, decision variables for signal optimization are cycle time, green splits and phase sequence, whereas appropriate path flow distribution is a decision variable for the DUE problem. Both the problems are solved simultaneously. It is easier to identify the convergence to the optimal solution. Whereas, in the bi-level programming problem, signal optimization is the upper-level problem and DUE assignment is the lower-level problem. As the DUE assignment procedure is iterative, bi-level programming approach requires longer time and also it is difficult to identify whether the iterations are converging to the optimal solution. The associated objectives may not always act in tandem. Moreover, looking to the necessity of solving DTA problem for on-line deployment with faster computational tractability, joint optimization approach is more preferable to adopt compared to the bi-level programming. Considering this, in this paper an attempt has been made to solve this problem as a joint optimization problem and that is also using an artificial intelligence technique of GAs.

2. Joint optimization problem

In this paper predictive dynamic user equilibrium (PDUE) condition is considered, in which user chooses a route that minimizes his/her actual travel time along the route to his destination. The definition and formulation of PDUE condition, mesoscopic simulation using DTASP and modified MSA for arriving PDUE condition are given in Varia and Dhingra, 2004. In the same reference, PDUE problem is solved for the tentatively fixed pretimed signal timings and phase sequences using modified MSA. Signal setting parameters have been assumed constant during the analysis period, whereas the only path flow distribution factor (λ) has been changed to arrive up to PDUE condition. Now, in this paper both the decision variables are selected in such a way that the PDUE condition can be maintained during the analysis period. However, optimal signal setting parameters are kept constant during the analysis period of peak hour considering that there are no such considerable variations in the O-D demand flow of each O-D pair.

In the joint optimization problem, for the signal setting parameters, optimum cycle length, green time splits according to flows on the approaches, phasing and phase sequences, offsets between consecutive signalized intersections etc. are required to be set in such a way that delays due to signalized intersections in the network shall be minimum. At the same time proportion of traffic flow on each link/path shall be such that travel cost/actual travel time of users in the network shall be minimum. To obtain the optimum cycle length and green splits, any of the available methods like, Webster's formula (1958), Australian Road Capacity Guide Method (ITE, 1982), Highway Capacity Manual Method (1985) is being used generally. These methods are good enough for isolated intersections. Whereas, for the congested network having number of signalized intersections, phase sequences, offsets and management of turning movements are also required to be considered. For this purpose, softwares like TRANSYT, SCOOT for static assignment and CONTRAM, DYNASMART for DTA can be used. In the proposed study genetic algorithm approach is used to select the optimum cycle, green splits and phase sequence simultaneously with the optimal path flow distribution factor (λ) to solve a joint optimization problem. The GAs are stochastic algorithms and can find close to optimal solution of the noisy, discontinuous or complex objective functions faster than the conventional optimization methods (Goldberg, 1989, Deb, 1998).

In this proposed study, PDUE condition gives indirect measure of optimal signal setting parameters in the network, because it minimizes the difference of travel cost (actual travel time) between used and shortest path of the users in the system. Actual travel time in both the conditions is not only a function of delay due to signal setting parameters of the signalized intersections, but it also includes delays due to unsignalized intersections and vehicle interactions on links. These delays are the functions of path flow value also. Thus, the minimization of objective function of PDUE problem with the constraints of signal setting parameters will satisfy the signal optimization with PDUE condition. The formulation of joint optimization problem is given as follows:

$$\text{minimise } \ \mathrm{Z}(\mathrm{f}) = \sum_{\forall r,s,p,q} \int_{0}^{T} \left[\frac{\left| \eta_{rsp}(t)\,|_{f_{rsp}(t)} - \eta_{rsq}(t)\,|_{f_{rsq}(t)} \right|}{\theta_{rs}(t)} \right] (F,S)\, dt \qquad (1)$$

Subject to, (i) O-D demand flow constraints:

$$d_{rs}(t) = \sum_{p \in P_{rs}(t)} f_{rsp}(t) \qquad \forall\, r, s, t \qquad (2)$$

$$f_{rsp}(t) \geq 0 \qquad \forall\, r, s, t, p \in P_{rs}(t) \qquad (3)$$

(ii) Constraints of signal setting parameters:

$$\sum_{l=1}^{\Phi_n} y_{l\,n}(t) = 1 - L_n(t)/C_n(t) \qquad \forall\, n, t \tag{4}$$

$$y_{l\,n}(t)\,(C_n(t) - L_n(t)) \geq g_{l\,n}^{\min} \qquad \forall\, n, t \tag{5}$$

$$\text{Where, } \theta_{rs}(t) = \begin{cases} 1 & \text{if } \phi_{rs}(t) = 1 \\ \\ \phi_{rs}(t) - 1 & \text{if } \phi_{rs}(t) > 1 \end{cases} \tag{6}$$

(The notations, which are used to represent the variables, are shown in Appendix-I)

Minimization of the above objective function is carried out using GA optimizer and developed DTASP, which is discussed in the following section.

3. Solution using GA and DTASP

The LibGA software (version 1.00, developed at the Massachusetts Institute of Technology, USA) is used for GA application. Path flow distribution factor λ, green times and phase sequences of signalized intersections can be decided by GA optimizer to minimize the values of objective functions, whereas DTA can be carried out using DTASP. Figure 1 shows the developed DTASP procedure (Varia, Dhingra, 2004). In the developed DTASP, delays on the links due to vehicle interactions can be calculated with the help of speed-density relationship. Delays on unsignalized intersections can be calculated by simulating deceleration of platoons according to traffic condition, and the delays on the signalized intersections are taken into account by stopping the platoons in queue up to clearance, i.e., by queue formation and discharge according to signal settings. Thus, delay due to any change in signal setting parameter or path flow change is implicitly taken care by DTASP and there is no need of using delay model for signalized intersections. The DTASP gives actual travel time of platoons from origin to destination dynamically considering all effects due to change in the decision variables of the network. A flow-chart in the Figure 2 shows the procedure adopted to solve the joint optimization problem.

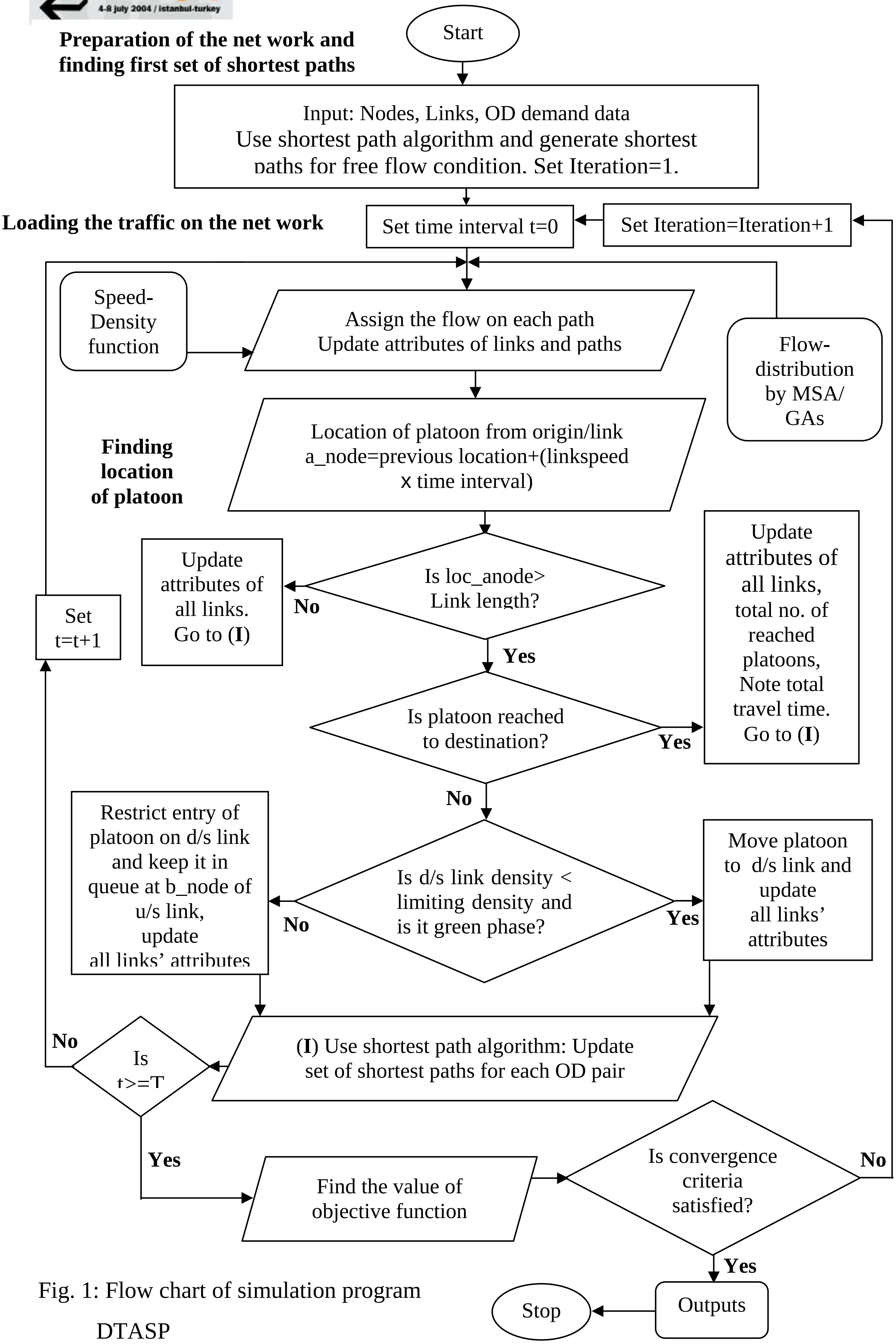

Fig. 1: Flow chart of simulation program DTASP

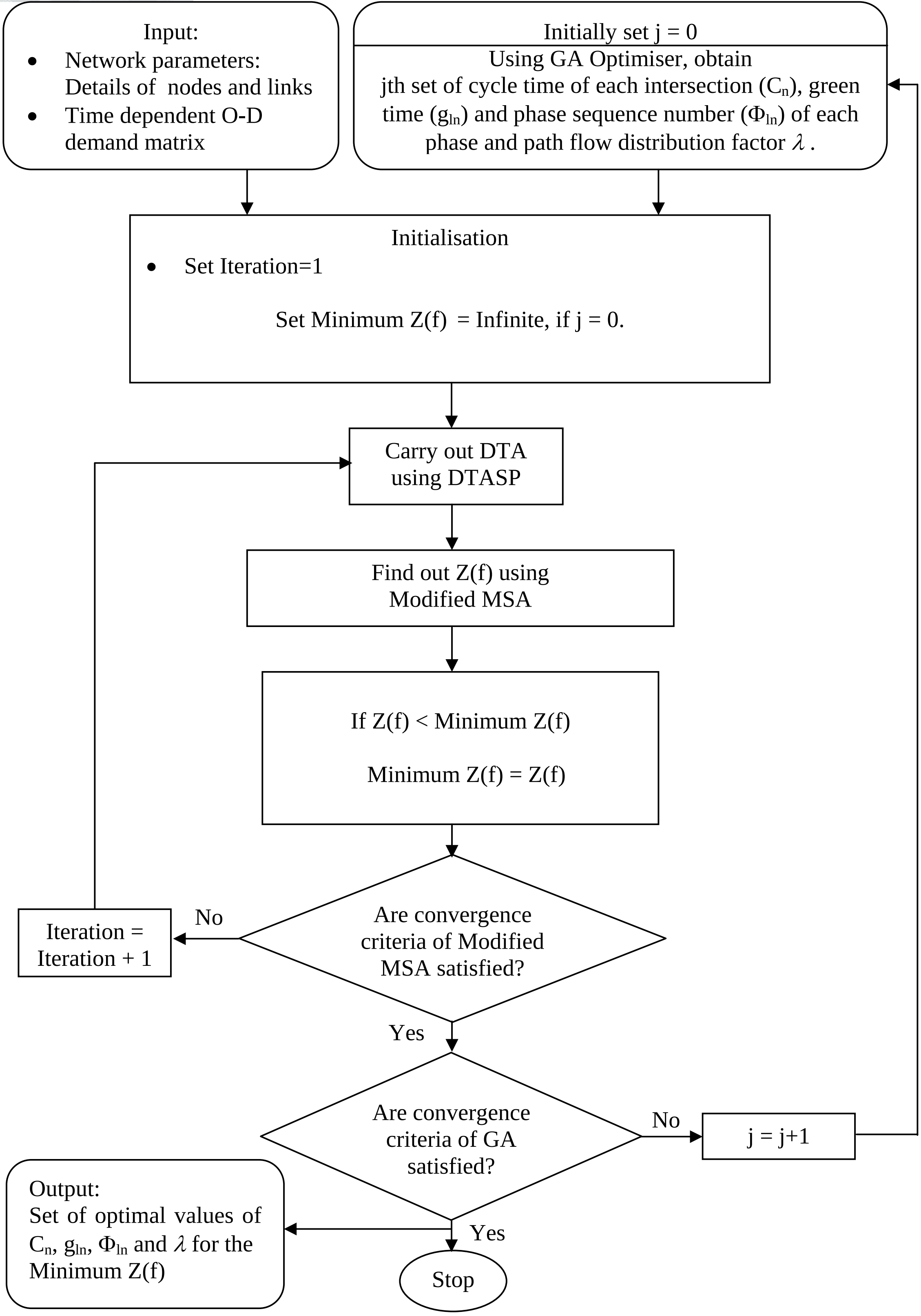

Fig. 2: Flow chart showing procedure of solving joint optimization problem.

The iterative procedure of path flow distribution for the different conditions in the modified MSA is given as follows (Varia, Dhingra, 2004):

Let $\mathrm{f}^{(\mathrm{n})} = \left\{ f_{rspt}^{(n)}\ \forall r,s,t,\ p \in P_{rst}^{(n)} \right\}$ be the path - flow vector at the nth iteration.

(1) First iteration $(n = 1)$:

$$f_{rspt}^{(n)} = \begin{cases} \lambda\, d_{rst} & \text{if } p = y_{rst} \\ \\ (1-\lambda)\, d_{rst}\, \alpha_{rspt}^{(1)} & \text{if } p \neq y_{rst} \end{cases} \qquad \forall r,s,t \qquad (7)$$

$$\text{where, } \alpha_{rspt}^{(1)} = \frac{\exp(-\beta_{rspt})}{\sum_{p} \exp(-\beta_{rspt})}$$

(2) Next iterations $(\mathrm{n} > 1)$:

(i) if $y_{rst} \in P_{rst}^{(n-1)}$

$$f_{rspt}^{(n)} = \begin{cases} \left(1 - \dfrac{\lambda k}{n+1}\right) f_{rspt}^{(n-1)} + \left(\left(\dfrac{\lambda k}{n+1} \right) d_{rst}\, \alpha_{rspt}^{(2)} \right) & \text{if } p = y_{rst} \\ \\ \left(1 - \dfrac{\lambda k}{n+1}\right) f_{rspt}^{(n-1)} & \text{if } p \neq y_{rst} \text{ and } p \in P_{rst}^{(n-1)} \\ \\ \left(\dfrac{\lambda k}{n+1} \right) d_{rst}\, \alpha_{rspt}^{(2)} & \text{if } p \neq y_{rst} \text{ and } p \notin P_{rst}^{(n-1)} \end{cases} \qquad \forall r,s,t \qquad (8)$$

$$\text{where, } \alpha_{rspt}^{(2)} = \frac{\exp(-\beta_{rspt})}{\exp(-\beta_{rsy_{rst}t}) + \sum_{p \notin P_{rst}^{(n-1)}} \exp(-\beta_{rspt})}$$

(ii) if $\; y_{rst} \notin P_{rst}^{(n-1)}$

$$f_{rspt}^{(n)} = \begin{cases} \left(\dfrac{\lambda k}{n+1}\right) d_{rst}\, \alpha_{rspt}^{(2')} & \text{if} \;\; p \notin P_{rst}^{(n-1)} \\ \\ \left(1 - \dfrac{\lambda k}{n+1}\right) f_{rspt}^{(n-1)} & \text{if} \;\; p \in P_{rst}^{(n-1)} \end{cases} \qquad \forall\, r, s, t \qquad (9)$$

$$\text{where,} \quad \alpha_{rspt}^{(2')} = \frac{\exp(-\beta_{rspt})}{\sum_{p \notin P_{rst}^{(n-1)}} \exp(-\beta_{rspt})}$$

(The notations, which are used to represent the variables, are shown in Appendix-I)

The proposed methodology is applied on example network with assumed peak hour demand flow. The details of example network and demand flow are given in following section.

4. Example network, demand flow and other parameters

Example network is shown in Figure 3. It consists of 3 zonal centroids, 11 intermediate nodes and 19 links. 3 links have one-way traffic on undivided two lanes. While remaining 16 Links have two-way traffic on divided four lanes (two lanes in each direction). All 19 links are converted into 38 unidirectional links to simplify the computation work. Required attributes are assigned to each link and each node in the program. Among the 11 intermediate nodes, 3 are assumed to have signalized intersections and remaining are assumed to have uncontrolled intersections. Traffic demands for peak one hour are assumed hypothetically for 6 OD pairs (1-8, 1-14, 8-1, 8-14, 14-1, 14-8), and graphically presented in Figure 4a – 4c.

The discrete time interval in the analysis is chosen as less than the length that a vehicle can traverse the shortest link with free flowing speed. In this example network, minimum time required to pass the shortest link with free flow speed is about 0.4 min. However, to reflect the real traffic conditions in better way, the length of time interval is adopted 0.1 min. The density at capacity is assumed to be 150 pcu/lane/km for all links. A speed-flow relationship is adopted from the *Mumbai Metro Study* (MMPG, 1997) to find the link-costs on the Example Network. The relation is given as follows:

$$V = V_f(1\text{-}\alpha(e^{\beta \ln(q/c)})) \qquad (10)$$

where, V = speed at any time interval
V_f = free-flow speed
c = link capacity
α, β = speed-flow parameters
q = flow at that time interval

For the purpose of link-cost function, above relationship is converted into speed-density function and then used in simulation program. The selection of other decision parameters for the example network is discussed here.

(1) *Signal cycle times*: For the three signalized intersections (node no. 4, 7 and 10) of the Example Network, minimum and maximum cycle length is assumed to be 100 sec and 112 sec respectively. These limits are decided according to demand flow variation. Total lost time is assumed to be 16 sec.

(2) *Green times*: Minimum and maximum green time is assumed to be 18 sec and 24 sec respectively. Minimum green time is decided as per the requirement of the pedestrians to cross the approach. These timings are kept in multiples of six, because the time interval for updating the network conditions is 0.1 min (6 sec) in the DTASP.

(3) *Phase sequence number*: For simplicity, straight and right turning movement of traffic on each approach is considered as one phase and green time is always given to the left turning movement (which is generally found in Indian traffic conditions). Thus, for the total twelve phases, twelve values of green times are to be selected. The progression of phasing is assumed to follow clockwise direction on each signalized intersection. So, if the phase sequence number of any one approach of signalized intersection is known, rest of the three numbers can be easily obtained. For example, if the phase sequence number of approach link 11 of the signalized intersection 4 is assumed to be 1, then the phase sequence numbers of links 34, 14 and 31 become 2,3 and 4 respectively. Therefore, only three phase sequence numbers are to be selected (one for each signalized intersection) for the example network. Optimal offsets between phases of consecutive intersections can be obtained implicitly when the PDUE condition is satisfied.

(4) *Path flow distribution factor* λ: It is observed that modified MSA is to be preferably adopted for getting PDUE condition faster compared to GA approach and procedure in the modified MSA can be carried out as per the Case 2 (Varia, Dhingra, 2004) as Case 2 has wider range of λ and also it requires moderate number of iterations (less than 50 iterations) to get close to optimal value of objective function. Range of λ can be kept between 0.5 $\lambda(temp)$ to 0.8 $\lambda(temp)$ (Varia, Dhingra, 2004). Selection of λ is carried out by GA optimizer for the above range, whereas the procedure of finding value of objective function for PDUE condition is carried out by modified MSA in the DTASP. As the value of $\lambda(temp)$ is taken 0.6 for the example network, the range of λ can be taken from 0.3 to 0.5.

Total chromosome length in GA optimizer is decided from the summation of three sub-string lengths. First sub-string includes twelve values of green times, where g_l^{min} = 18 sec and g_l^{max} = 24 sec. It requires minimum string length = 12 x 3 = 36 bits. Second sub-string includes three values of phase sequence number, where its value may be any one number from 0, 1, 2, and 3. It requires minimum string length = 3 x 2 = 6 bits. Third sub-string includes one value of λ, where the value of λ ranges from 0.3 to 0.5. It requires minimum string length of 1 x 5 = 5 bits. Thus, minimum chromosome length is required to be 47 bits.

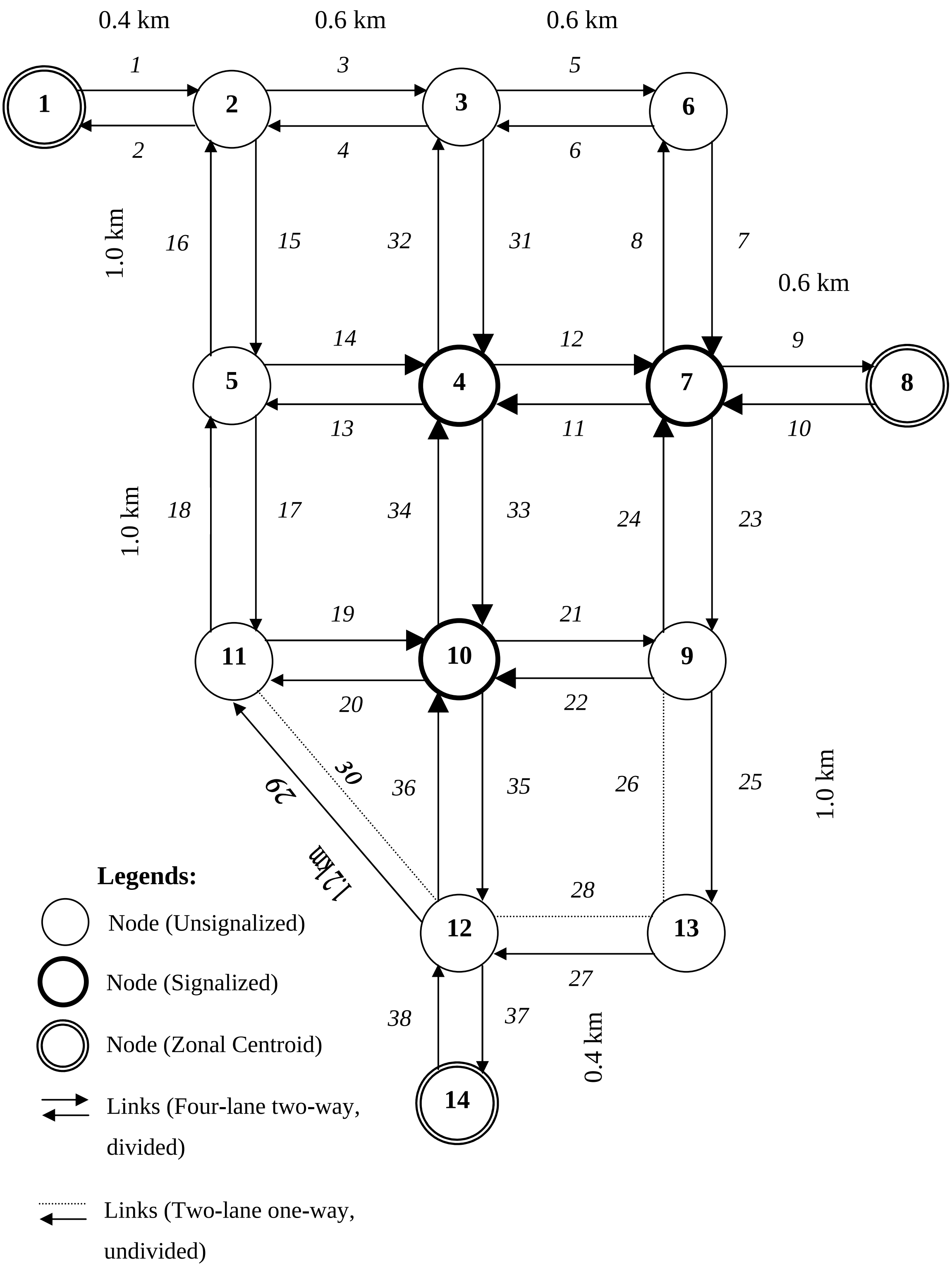

Fig. 3: Example network (Directed linear network).

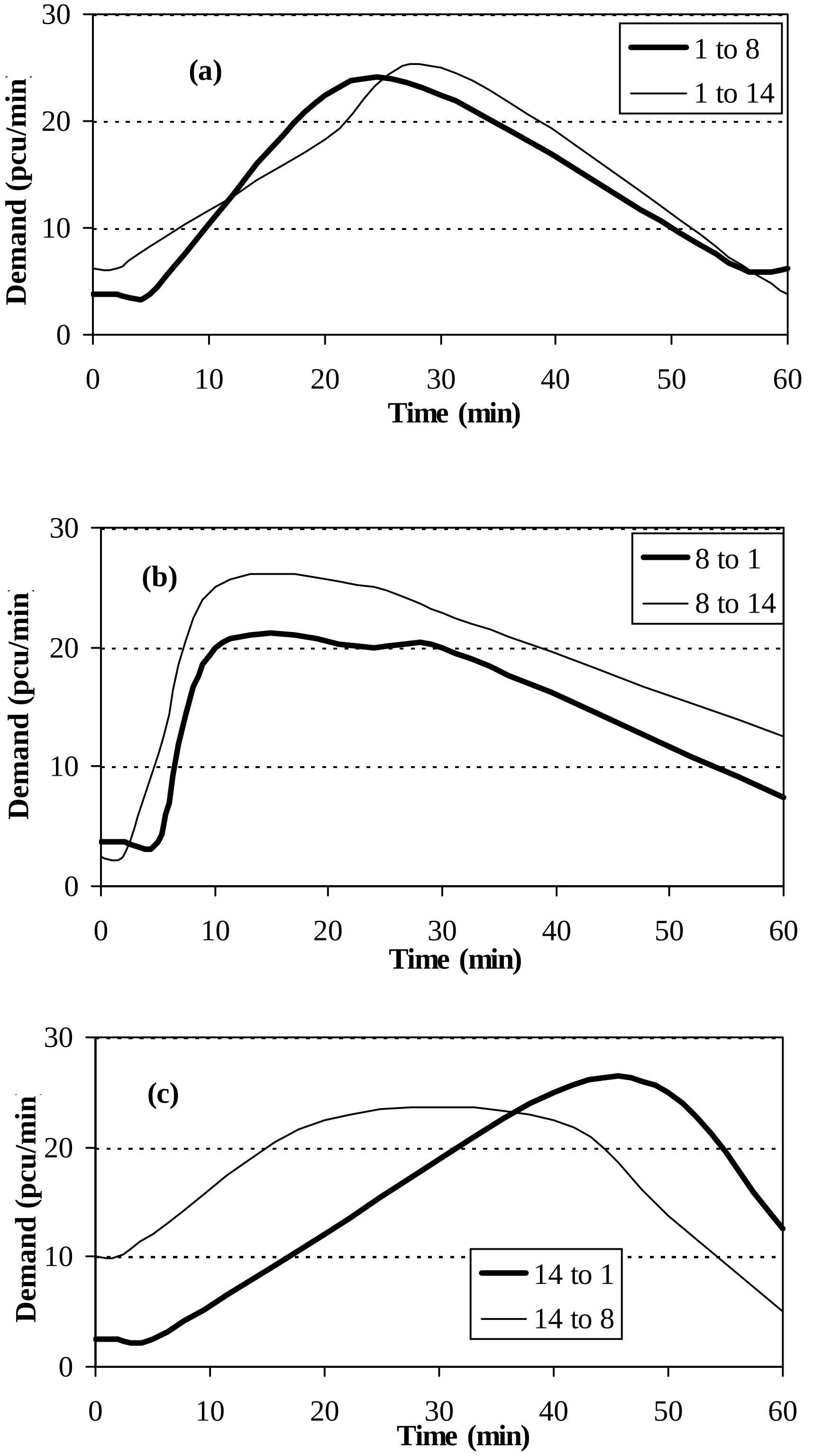

Fig. 4: Assumed traffic demand between O-D pairs; (a) 1-8 and 1-14, (b) 8-1 and 8-14, (c) 14-1 and 14-8.

When the summation of green times of all phases on the signalized intersection violates the range of cycle length-total lost time (i.e., $\Sigma g_{ln} > C_n^{max} - L_n$ or $\Sigma g_{ln} < C_n^{min} - L_n$), penalty is assigned to the value of objective function (i.e., to the value of fitness function in GA). So, the cycle time comes within the selected range and it avoids selection of cycle time separately. Convergence criteria for the modified MSA are decided from a gap function, which is given as

$$GAP^{(n)} = \frac{\sum_{r,s,t,p\in P_{rst}^{(n)}} f_{rspt}^{(n)} \left| \eta_{rspt}^{(n)} - \eta_{rsy_{rst}t}^{(n)} \right|}{\sum_{r,s,t} d_{rst}\, \eta_{rsy_{rst}t}^{(n)}} \times 100\% \qquad (11)$$

(i) Minimum 50 iterations of modified MSA are carried out, even if convergence gap obtained by equation (11) is less than 5% within 50 iterations. (ii) Otherwise, more than 50 iterations are carried out till the convergence gap is less than 5% (Tong, Wong, 2000). Same way the convergence criteria for the GA approach are considered as; (i) Minimum 50 generations are carried out, even if convergence is obtained within 50 generations (i.e., when all the fitness values in the pool are identical). (ii) Otherwise, more than 50 generations are carried out till convergence. It is observed that convergence is obtained within 50 iterations/generations.

Different GA parameters are decided after several runs for the proposed objective function of PDUE condition. The types of GA parameters like, uniform crossover, simple random mutation, roulette selection, seed value 1 and pool size of 80 have better performance compared to their respective alternatives. Out of the different crossover rates, crossover rate of 0.95 performed better with different mutation rates for the PDUE condition. The values of fitness functions, obtained for the same, are shown in the Table 1.

Table 1: The values of fitness function for the different crossover rate and mutation rate

Mutation rate	Crossover rate			
	0.8	0.9	0.95	1.0
0.01	1647.65	1641.4	1552.10	1600.07
0.02	1600.20	1602.80	1571.45	1598.60
0.03	1598.45	1612.30	1545.85	1589.50
0.04	1602.15	1630.20	1587.90	1607.60
0.05	1647.65	1647.65	1578.95	1611.50
0.06	1587.20	1615.70	1578.95	1605.30
0.07	1578.90	1590.35	1552.10	1584.20
0.08	1564.55	1551.17	1590.15	1538.65
0.09	1664.50	1624.15	1639.35	1602.40
0.1	1678.2	1589.25	**1537.70**	1589.25
0.2	1715.20	1590.50	1545.85	1570.50

5. Exhaustive search technique and comparison of results

An exhaustive search technique is applied for this condition to confirm that whether the result of GA approach converges to the right solution or not. All possible combinations of three decision parameters (green times, phase sequences and path flow distribution factor λ) are applied to the DTASP. Optimization is carried out using the modified MSA. Total combinations are as follows:

- Path flow distribution factor λ = {0.3, 0.31, 0.32, …… , 0.5} = Total 21 options,
- Green times = {18 sec, 24 sec}, maximum cycle = 112 sec and minimum cycle = 100 sec, total lost time = 16 sec, total phases = 4. These parameters give 11 feasible sets of green times on one signalized intersection. So, total options for the three intersections = 11 x 11 x 11 = 1331
- Phase sequence numbers = {0, 1, 2, 3}. As the phases are considered to follow clockwise progression, feasible 4 sets can be obtained on one intersection. So, total options for the three intersections = 4 x 4 x 4 = 64.
- Overall combinations = 21 x 1331 x 64 = 1788864.

Global minimum value of objective function is obtained from all the above combinations and it is found that the same value is obtained by GA approach for the crossover rate = 0.95 and mutation rate = 0.1. Computation time required in GA approach is quite lesser, approximately 1/50th than it is required for the exhaustive search method. Sets of optimal values of decision parameters obtained for the PDUE condition is shown in the Table 2. Table 3 shows the initially tentatively fixed signal settings. The optimal values of objective functions for the optimum signal settings are considerably improved/minimized than the optimal values obtained for the tentatively fixed signal settings. This comparison is given in Table 4. Actual travel time experienced by the platoons of O-D pair 1-14 for the tentatively fixed and for the optimized signal setting parameters are shown in Figure 5 and 6. It can be observed that the difference between actual travel times on all used paths is very small, as it is in PDUE condition. It is also evident that actual travel time is reduced for the optimum signal settings, compared to that obtained for the tentatively fixed signal settings. The paths developed between O-D pair 1-14 are; path1: 1-2-3-4-10-12-14, path 2: 1-2-5-11-10-12-14 and path 3: 1-2-5-4-10-12-14.

Table 2: The sets of optimal values of decision parameters

Node No.	4				7				10			
Link No.	14	31	11	34	10	24	12	7	22	36	19	33
PDUE problem: Path flow distribution factor λ = 0.32												
Cycle (sec)	100				100				100			
Green (sec)	18	18	24	24	18	18	24	24	24	18	18	24
Phase Sequence No.	1	2	3	0	3	0	1	2	3	0	1	2

Table 3: The details of tentatively fixed signal setting parameters

Node No.	4				7				10			
Link No.	14	31	11	34	10	24	12	7	22	36	19	33
Cycle (sec)	112				112				112			
Green (sec)	24	24	24	24	24	24	24	24	24	24	24	24
Phase Sequence No.	3	0	1	2	0	1	2	3	0	1	2	3

Table 4: Improvement due to signal optimization

	DTA without signal optimization	DTA with signal optimization	Improvement due to signal optimization (%)
Minimum value of objective function	2091.00	1537.70	26.46
Convergence gap (%)	2.584	2.185	15.44
Total vehicles reached the destinations in 1 hour (%)	93.529	93.621	0.09
Average travel time of platoons to reach the destinations (min)	7.509	7.247	3.49

6. Conclusion and further scope of work

Optimization of signal setting parameters with PDUE condition is carried out simultaneously using GA and modified MSA as a joint optimization problem. This approach has given very promising results. For the given range of parameters, GA has obtained the global optimum value of the fitness function within a considerably reduced computation time compared to the exhaustive search technique for all possible combinations. With the optimization of signal setting parameters, value of objective function in PDUE problem reduces to about 26% when compared with the values of tentatively fixed signal settings and considerable reduction in actual travel time is observed.

It can be concluded that optimization of signal setting parameters can reduce the travel time of users considerably in the network. Optimization of not only the signal cycle time and green splits, but also of the phase sequence and phase offset is significant to reduce the travel time in the network. Simultaneous optimization of signal setting parameters and PDUE condition is found better using GA and DTASP with modified MSA, as it converges to the optimal solution with lesser computation time than the exhaustive search method.

The proposed methodology is applied on the example network of small size, only for the private vehicle trips and that for the traffic control or traffic management/improvement point of view. It shall be tested on large size real-life network, not only for the traffic control but also for testing the route choice behavior and departure/arrival time selection behavior of trip makers.

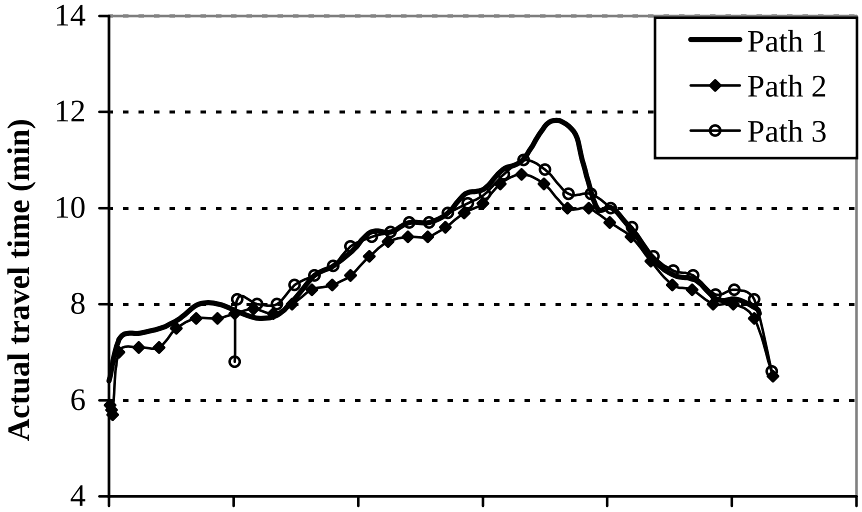

Fig. 5: Actual travel time experienced by platoons of the O-D pair 1-14 for the tentatively fixed signal setting parameters.

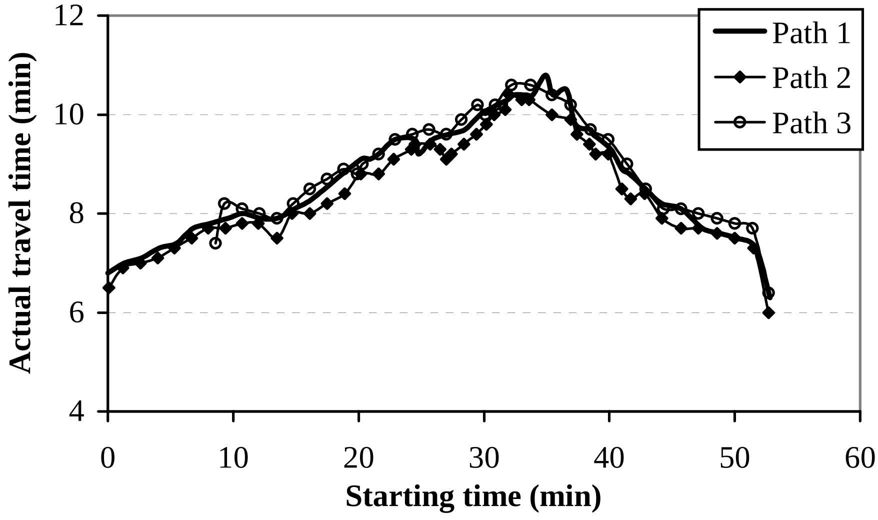

Fig. 6: Actual travel time experienced by platoons of the O-D pair 1-14 for the optimized signal setting parameters.

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Appendix-I: Nomenclature

a_node = entrance node of link

b_node = exit node of link

C_n = signal cycle time (sec) of n^{th} intersection

$C_n(t)$ = signal cycle time (sec) of n^{th} intersection during the time interval t

DTA = dynamic traffic assignment

DTASP = dynamic traffic assignment simulation program

$d_{rs}(t)$ = demand flow between O-D pair r-s at the time interval t

d_{rst} = number of vehicles travelling between O-D pair r-s, departing from the origin during the t^{th} time interval

F = the set of path flow = $\{f_{rspt}\}, \forall\ r, s, p, t$

$f_{rsp}(t)$ = traffic flow between the O-D pair r-s via path p, entered to the network through origin at the time interval t

$f_{rspt}^{(n)}$ = number of vehicles travelling on path p between O-D pair r-s, departing from the origin during the t^{th} time interval of n^{th} iteration

GA = genetic algorithm

g_{ln} = green time (sec) of the l^{th} phase on n^{th} intersection

g_{ln}^{min} = minimum green time (sec) required for the l^{th} phase on n^{th} intersection

$L_n(t)$ = lost time at intersection n during time interval t

loc_anode = location of platoon from a_node of link

MSA = method of successive averages

O-D = origin to destination

PDUE = Predictive dynamic user equilibrium

$P_{rs}(t)$ = set of paths between O-D pair r-s at the time interval t

$P_{rst}^{(n)}$ = set of paths between O-D pair r-s at the time interval t during the n^{th} Iteration

S = the set of signal setting parameters = $\{\ y_{lnt}\ \}, \forall\ l, n, t$

T = total duration of analysis period

t = time interval number

T_{rspa_m} = arrival time at destination s, i.e. exit end of the last link a_m on path p between O - D pair $r - s$

$y_{ln}(t)$ = green time proportion for phase l at intersection n during time interval t

y_{rst} = the shortest path developed between O-D pair $r - s$ during the t^{th} time interval

Z(f) = value of objective function at PDUE condition

α_{rspt} = logit flow distribution factor on path p between O-D pair r-s at the t^{th} time interval

β_{rspt} = instantaneous travel time on path p between O-D pair r-s, when vehicles embarked on to the network at the time interval t

λ = flow distribution factor (used to decide proportion of demand flow to be assigned on the shortest path of a given O-D pair)

$\lambda(temp)$ = flow distribution factor obtained after rough estimate

$\eta_{rsp}(t)|_{f_{rsp}(t)}$ = actual travel time on path p between O - D pair $r-s$, for the traffic flow $f_{rsp}(t)$ entered on to the network at the time interval t

$\eta_{rspt}^{(n)}$ = actual travel time on path p between O-D pair r-s, for the vehicles embarked on to the network at the time interval t during the n^{th} iteration

$\eta_{rsq}(t)|_{f_{rsq}(t)}$ = actual travel time on path q between O - D pair $r-s$, for the traffic flow $f_{rsq}(t)$ entered on to the network at the time interval t, where path q has minimum actual travel time among the all used paths of O - D pair $r-s$ for the time interval t

$\theta_{rs}(t)$ = averaging factor of O-D pair r-s for the time interval t

Φ_{ln} = phase sequence number of the l^{th} phase on n^{th} intersection

$\phi_{rs}(t)$ = total number of paths developed between O-D pair r-s at the time interval t from the beginning

∞ = infinite

l = subscript for phase

n = subscript for intersection

p,q = subscript for path

r = subscript for origin node

s = subscript for destination node

n = superscript for iteration number