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An Isolated Traffic Signal Design using a GA-based Optimization Technique

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***Abstract:** The Genetic Algorithm (GA) approach is an evolutionary optimization technique, which is developed based on the fundamental theories of natural selection and evolution. The present study focuses on the design of an isolated traffic signal for a two-phase intersection using the conventional method and GA-based optimization technique for unsaturated traffic flow conditions. The methodology of the study includes formulation of an objective function and the constraints, formulation of the constraint violation coefficient, formulation of the modified objective function, formulation of the fitness index (fi), and the GA operations to determine the best green signal timings. The intrinsic nature of Genetic Algorithms in performing elitism, which assures to carry forward the best solution identified in each generation to the next generation. An example problem was solved to demonstrate elitism using binary genetic algorithm with a single variable approach. In the GA operation, parent strings/chromosomes are selected and the crossover is performed along with mutation to form the new offspring's. Mutation helps in avoiding the convergence of the solution to local optima. In this operation Fitness Index (FI) values of each strings/chromosomes are used as a measure to identify the parent strings to perform GA operations for the next generation. The results of the study indicate that the proposed technique can be used to optimize the signal timings of an isolated traffic signal, this will influence on reducing the delays at the junctions.*

***Keywords:** Genetic Algorithm, Isolated Traffic Signal Design, Webster, Optimization, Green Signal Time, Cycle Time.*

I. INTRODUCTION

The genetic algorithm (GA) approach in problem-solving scenarios is an emerging optimization technique, which was formulated based on the theories of natural selection and evolution. Genetic Algorithms are capable of identifying the global optima solution over a wider solution space instead of the local-optima solution. The optimization problems with disconnected search spaces are easy to handle using the GA technique. In the case of gradient-related search techniques, the use of complex mathematical relationships and their derivatives are not required for determining the optima [1].

On the other hand, simulation-related algorithms are guided by the measure of performance to ensure a feasible solution near to the global optima [2]. Fogel, Gen and Cheng, Goldberg, Haupt, Miller and Thompson, and Mitchell provide the theoretical aspects on GAs [1], [3]-[7].

The use of GAs for the optimization-based problems is an emerging technology in various fields of engineering, such as in software engineering, urban transport planning, machine learning, electronic circuit design, transit network design, image processing, traffic management, multimodal optimization, and accident studies.

The initial part of the present study deals with the isolated traffic signal design using conventional Webster's method and later part of the study focused on the application of a GA-based optimization technique in designing a two-phase traffic signal.

In the two-phase isolated traffic signal design using the GA approach, search for an optimum green time stipulates the basic operation of elitism that ensures the best solution of each generation is carried forward to the next generation.

A fitness index (FI) determined based on the computation to minimize the delays using single variable binary GA-based technique assists in the selection of strings/chromosomes with non-optimal solution values and on such strings/chromosomes cross-over and mutation operations were performed to generate new offspring's. Using binary and real coded variables in C, a GA developed by K. Deb [8] was adapted and modified to fit the present study objective and used to design an isolated traffic signal.

II. A BRIEF LITERATURE REVIEW

The GA-based technique has been used in the field of transportation, such as in the identification of activity plans [9], identification of zone boundaries [10], transit network design [11], [12], traffic incident detection [13], and dynamic traffic management [14], [15].

Foy et al. were used GAs to determine the traffic signal timing for the first time [16]. The average delay was minimized to obtain the near-optimal solution. For oversaturated traffic conditions Park et al. proposed a GA-based optimization program to design a traffic signal [17]. Braun et al. performed studies on an evolutionary optimization technique to design a network with coordinated fixed-time controllers [18]. Stevanovic et al. proposed the application of the GA-based technique for the optimization of signal timing with microsimulation modeling using VISSIM [19].

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III. THEORETICAL ASPECTS OF ISOLATED SIGNAL DESIGN

In the design of an isolated traffic signal, the time duration between the starting of green signal time for one phase and the start of the succeeding green signal time for the same phase refers to cycle time (C), can be expressed according to Webster and Cobbe as [20],

$$C = \sum_{i=1,n} g_i + L \qquad (1)$$

where, g_i = *green signal time* for phase i; and L = the total *time lost* due to junction clearance and startup for a cycle. Can also be expressed as,

$$\sum_{i=1,n} g_i = C - L \qquad (2)$$

The effective green signal time (g_i) for phase i is assumed to lie within the lower and upper limits g_{min} and g_{max}, and can be expressed as,

$$g_{min} \leq g_i \leq g_{max} \qquad (3)$$

where, g_{max} = the maximum effective green signal time, for phase i, it refers to the total time duration required for vehicles to cross a junction and g_{min} = the minimum green signal time, which was assumed as 10 seconds as per IRC:93 [21]. For a minimization problem (3) can be re-written in the form $g(x) >= 0$ as,

$$g_i - g_{min} >= 0 \text{ and } g_{max} - g_i >= 0 \qquad (4)$$

The maximum green signal time g_{max} can be expressed in terms of the minimum green signal time $g_{j\ min}$ for the junction j, and the time lost L as,

$$g_{max} = C - g_{j\ min} + L \qquad (5)$$

The total time lost L is expressed according to Webster and Cobbe as [20],

$$L = \sum L_i + \sum (I_i - a_i) \qquad (6)$$

where, L_i = the time lost due to starting delays for each phase i; I_i = inter-green time for each phase i; a_i is the amber time for each phase i.

The maximum effective green signal time for signal phase i based on (5) can then be expressed as,

$$g_{max} = C - \{g_{j\ min} + [\sum_{i=1,\ n} L_i + \sum_{i=1,\ n} (I_i - a_i)]\} \qquad (7)$$

The above equation can be written as,

$$C = g_{max} + \{g_{j\ min} + [\sum_{i=1,\ n} L_i + \sum_{i=1,\ n} (I_i - a_i)]\} \qquad (8)$$

According to IRC:93, for each phase L_i and Ii are assumed as 2s and 4s respectively [17]. The total time lost can then be computed from (6) as,

$$L = \sum_{i=1,} L_i + \sum_{i=1,\ n} (I_i - a_i) = (2+2)+[(4-2)+(4-2)] = 8\text{s} \qquad (9)$$

In the design of an isolated signal, the *cycle time C* can be assumed to lie within the minimum and maximum cycle time C_{min}, and C_{max}, and is expressed as,

$$C_{min} \leq C \leq C_{max} \qquad (10)$$

For a minimization problem, the above equation (10) can be re-written in the form $g(x) >= 0$ as,

$$C - C_{min} \geq 0, \text{ and } C_{max} - C \geq 0 \qquad (11)$$

Based on (5), the equation for the minimum cycle time can be expressed as,

$$C_{min} = g_{max} + [g_{j\ min} + L]$$

Here, in the computation of minimum cycle time, only g_{min} is considered by ignoring g_{max}. Also, in the isolated traffic signal design for a junction, j can be assumed as unity. Hence, the above equation reduces to,

$$C_{min} = g_{min} + L \qquad (12)$$

Substituting for L in (12), we get,

$$C_{min} = g_{min} + \sum_{i=1,\ n} L_i + \sum_{i=1,\ n} (I_i - a_i) \qquad (13)$$

Assuming g_{min}= 10s; a_i= 2s, I_i= 4s; L_i= 2s; as per IRC:93 and HCM we get [21], [22],

$$C_{min} = 18\text{s};\ C_{max} = 120\text{s} \qquad (14)$$

Thus, the lower and upper limits for C_{min} and C_{max} are established. According to Webster and Cobbe, the effective green signal time for phase i is given as [20],

$$g_i = \{(C_o - L)\ y_i\} / Y \qquad (15)$$

where, C_0 = effective cycle time; L = time lost per cycle; y_i = maximum critical flow ratio ($q_{i\ max}/ S_i$); S_i = saturation flow in passenger car units per second (PCU/s); and Y = sum of critical flow ratios = $\sum y_i$.

IV. CONVENTIONAL (WEBSTER'S) METHOD IN THE DESIGN OF AN ISOLATED TRAFFIC SIGNAL

A two-phase junction with traffic volumes q_i and saturation volumes s_i for each phase i as shown in **Fig. 1**, the volume ratios y_i for each phase i are computed in **Table-I**. The sum of the maximum volume ratios in the North-South and East-West directions are thus given as,

$$Y = \text{Max } y_i\text{, N-S} + \text{Max } y_i\text{, E-W} \qquad (16)$$

$$= 0.375+0.283 = 0.658$$

Also, the minimum inter-green time I_i and the amber time a_i can be assumed as 4s and 2s respectively as per IRC:93 [21]. Additionally, the time lost L_i for each phase i is assumed as 2s. Thus, the total time lost per cycle can be computed using (6) as,

$$L=\sum L_i+\sum(I_i-a_i)=[(4-2)+(4-2)]+(2+2) = 8\text{s}$$

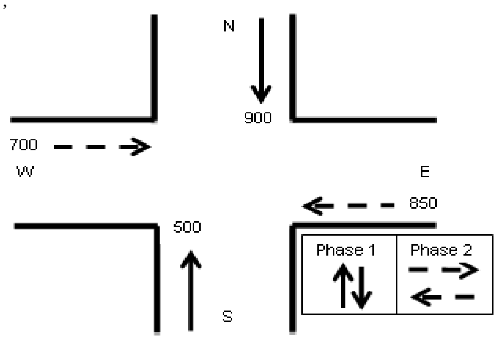

Fig. 1. Phasing Diagram for an Isolated Traffic Signal

The optimal cycle time (C_o) is determined based on Webster and Cobbe as [20],

$$C_o = (1.5\,L + 5) / (1–Y) \quad (17)$$

$$= ((1.5 \text{ x } 8) + 5) / (1 – 0.658)$$

$$= 49.70 \approx 50\text{s}$$

The total effective green signal time g is the sum of the effective green signal timings g_1 and g_2 for phases 1 and 2, which can be expressed as Webster and Cobbe [20],

$$g = g_1 + g_2 = C_o – L \quad (18)$$

$$= 50 – 8 = 42\text{s}$$

Table-I: Traffic Volume Details at the Junction

Phase	Phase 1		Phase 2	
Direction	**North (N)**	**South (S)**	**East (E)**	**West (W)**
q_i (vehicles/hr)	900	500	850	700
q_i (vehicles/s)	0.25	0.138	0.236	0.194
s_i (vehicles/hr)	2400	2400	3000	3000
s_i (vehicles/s)	0.666	0.666	0.833	0.833
$y_i = q_i / s_i$	0.375	0.207	0.283	0.233
Max y_i	0.375 Max $y_{i\text{, N-S}}$		0.283 Max $y_{i\text{, E-W}}$	
$Y = \sum$ Max y_i	0.658			

The effective green signal timings g_1 and g_2 for phase 1 (North-South direction) and phase 2 (East-West direction) can be determined as per Webster and Cobbe, for each phase i the effective green signal time can be computed as [20],

$$g_i = \{(C_o – L)\, y_i\} / Y \quad (19)$$

where, C_0 = effective cycle time; L = time lost per cycle; y_i = maximum volume ratio ($q_{i\,max}$/ S_i) for phase i; $S_{i=}$ saturation volume in PCU/s; and Y = sum of maximum volume rations = $\sum y_i$. Thus,

$$g_1 = \{(C_o–L) \text{ Max } y_{i\text{ ,N-S}}\}/Y \quad (20)$$

$$= 0.375\text{x}(50–8)/0.658 = 24\text{s}$$

$$g_2 = \{(C_o –L) \text{ Max } y_{i\text{ ,E-W}}\}/Y \quad (21)$$

$$= 0.283\text{x}(50–8)/0.658 = 18\text{s}$$

The effective green signal timings computed using conventional (Webster's) method for phases 1 and 2 are summarized in **Table-II**. The signal timing distribution diagram for the two-phase signal can be derived as shown in **Fig. 2**.

Table-II: Optimal Green Signal Timings Based on Conventional Webster's Method

Phases	Green Signal Timings Computed Based on the Conventional Webster's Method (s)
North-South (Phase 1)	24
East-West (Phase 2)	18

Fig. 2. Optimal Green Signal Timing for a Two-Phase Signal

V. FORMULATION OF OBJECTIVE FUNCTION AND CONSTRAINTS FOR A GA-BASED OPTIMIZATION TECHNIQUE

The computation of delay using Webster's equation is expressed as [23],

$$d_i = d_{uniform} + d_{random} – \text{correction term} \quad (22)$$

where, $d_{uniform}$ = delay due to uniform arrival of vehicles at the junction = $[C\,(1–\lambda)^2] / [2(1–\lambda x_i)]$; and d_{random} = delay due to random arrival of vehicles at the junction = $x_i^2/2.q_i\,(1–x_i)\}$.

The delay for phase i can be computed as,

$$d_i=\{[C(1\text{-}\lambda)^2]/[2(1\text{-}\lambda x_i)]\}+E[Q]/q_i–[0.65(C/q_i^{\,2})^{1/3}.x_i^{(2+5\lambda)}] \quad (23)$$

where C = cycle time in seconds; λ = effective green signal time proportion for each phase per cycle time = g_i/C; g_i = effective green signal time for phase i; x_i = degree of saturation for phase $i = q_i/(\lambda s_i)$ or q_i/c; q_i = mean arrival rate of vehicles expressed as PCU/s; s_i = saturation volume in PCU/s for phase i; and c = capacity of lane group = λs_i; $E[Q]$ = expected queue length = $x_i^2/[2.q_i(1–x_i)]$; and d_i = average delay for phase i per vehicle in seconds.

In deriving for the above equation, Poisson arrival and deterministic departures were assumed in which the variance to mean ratio was equal to unity.

The third term in the above equation is a correction term and it is considered to reduce the computed delay by 10% based on Webster's delay model [24].

Thus the final form of Webster's delay equation for each vehicle can be expressed as,

$$d_i = 0.9\,\{d_{uniform} + d_{random}\}, \text{ or} \quad (24)$$

$$d_i = 0.9\{[C\,(1–\lambda)^2] / [2(1–\lambda x_i)] + x_i^2/2.q_i\,(1–x_i)\} \quad (25)$$

Using (25) Webster's delay equation, it is possible to formulate the GA-based optimization problem that minimizes the delays at road junctions for unsaturated traffic flow conditions [23]. An optimization problem includes the formulation of an objective function, equality or inequality constraints, computation of individual parameter values, and evaluation of fitness indices [25].

In this optimization problem, it is required to formulate the objective function *f(x)* which aims in minimizing vehicular delays in the design of isolated traffic signals. An objective function *f(x)* was formulated based on minimizing the average delay per vehicle as,

$$Min\ f(x) = Min\ D = Min\ [(\sum_{i=1,n} q_i.d_i) / (\sum_{i=1,\,n} q_i)] \quad (26)$$

where, $f(x) = D$ = average delay per vehicle, which is a function of q_i, the mean arrival rate of vehicles in phase i, expressed in PCU/s. The value of D is computed as,

$$D = [(\sum_{i=1,n} q_i.d_i) / (\sum_{i=1,\,n} q_i)] \quad (27)$$

To determine the best green signal time using a GA-based approach, the constraints related to the green signal timing and the cycle time are formulated in addition to the non-negativity constraints. The details on the same are provided below.

A. Constraint related to the cycle time

$$C_{min} \le C \le C_{max} \quad (28)$$

In the present study, a near-optimal cycle time (C) of 50 seconds was assigned in the program, which falls within the minimum and maximum limit for cycle time. C_{min} was computed as18s using (12) and C_{max} was assumed as 120s as per recommendations of IRC:93 [21].

B. Constraints related to the green signal time

$$g_{i\,min} \le g_i \le g_{i\,max;} \text{ or,} \quad (29)$$

$$g_i - g_{i\,min} \ge 0; \text{ and } g_{i\,max} - g_i \ge 0 \quad (30)$$

where, g_i = the effective green signal time for phase i; $g_{i\,min}$ = minimum effective green signal time assumed as 10s according to IRC:93 [21]; and $g_{i\,max}$ = maximum effective green signal time computed as 32s using (7).

It is also required to add a *phase priority constraint* that signifies the phase with higher vehicular volume must possess a higher value of effective green signal time, expressed as,

$$g_1 - g_2 \ge 0 \text{ if } q_1 > q_2 \quad or \quad g_2 - g_1 \ge 0 \text{ if } q_2 > q_1 \quad (31)$$

C. Non-negativity constraints

$$g_i \ge 0; \text{ and } C \ge 0 \quad (32)$$

The effect of non-negativity constraint on the effective green signal time and cycle time becomes redundant as the lower and upper limits for the same were assigned in the GA program.

VI. FORMULATION OF THE CONSTRAINT VIOLATION COEFFICIENT

The aim of the present study is to determine the optimal green signal timings for the two-phase isolated traffic signal. The constraint violation coefficient (P_i) indicates the suitability of a particular green signal timing based on the violation of constraints related to the green signal time and the cycle time. The constraint violation coefficient (P_i) can be set to zero when a constraint $G_i(x)$ is satisfied, otherwise, the constraint $G_i(x)$ is violated and the value of P_i may be set to the value of $G_i(x)$. This can be expressed as,

$$P_i = G_i(x), \text{ if } G_i(x) > 0; \text{ and } P_i = 0, \text{ if } G_i(x) \le 0 \quad (33)$$

The sum of the constraint violation coefficients for a set of m constraints can then be expressed as,

$$P = \sum_{i=1,m} P_i \quad (34)$$

The sum of constraint violation coefficient (P) thus represents the penalty for the overall degree of violation.

VII. FORMULATION OF THE MODIFIED OBJECTIVE FUNCTION

To incorporate the effect of the overall degree of violation determined as the sum of constraint violation coefficient (P), a *modified objective function* $F(x)$ or $\eta(x)$ need to be formulated based on the similar approach adopted by Rajeev and Krishnamoorthy [26]:

$$\eta(x) = F(x) = f(x)\ (1 + KP) \quad (35)$$

where, $\eta(x)$ = penalty function as equal to $F(x)$; $F(x)$ = modified objective function; $f(x)$ = objective function; and K = scaling constant, assumed based on the influence of sum of constraint violation coefficient (P) on the objective function. In this study, scaling constant (K) was assumed as 10. The modified objective function values were computed for all the strings/chromosomes for the present generation.

VIII. FORMULATION OF THE FITNESS INDEX (FI)

The fitness index values define the feasibility and influence of each string/chromosome in the present generation.

$$FI_i = (\eta_{(x)max} + \eta_{(x)min}) - \eta_{(x)\,i} \quad (36)$$

where, FI_i is the fitness index of each strings/chromosomes; $\eta_{(x)i}$ is the modified objective function value for the same under consideration; $\eta_{(x)min}$ and $\eta_{(x)max}$ are the minimum and maximum values of $\eta_{(x)i}$ for individual strings/chromosomes of the present generation.

IX. GA OPERATIONS TO DETERMINE THE BEST GREEN SIGNAL TIMINGS

The following steps indicate the operations performed in the GA-based optimization technique:

- Encoding of binary strings/chromosomes for the initial sample space considering the effective green signal time, a minimum green signal time of 10s was considered as per IRC:93 recommendations [21] and a maximum green signal time of 32s was computed using (7). In the computation of actual string values, an approach suggested by Ceylan and Bell was adopted [27].
- The uniform and random delays were computed using (24) and the value of an objective function was determined by adding the delays in each phase as in (25).
- The green signal time constraints were computed based on (30) and the constraint violations for *phase priority constraints* were computed based on (31), in addition to the determination of total constraint violations using (34).

- The modified objective function values were computation based on (35) and the fitness indices for each of the strings/chromosomes were obtained using (36) for the present generation.
- The best strings/chromosomes with high fitness index values were selected and the characteristics of such strings/chromosomes were preserved to indicate the *elitism*.
- Genetic operations such as *crossover* and *mutation* were performed with the probability of 80% and 10% respectively on the remaining strings/chromosomes of the present generation to form new offspring's for the next generation. After a number of iterations, the best strings/chromosomes which represent the global optima were identification and the *effective green signal timing* was computed.

In a single variable GA-based technique for two-phase traffic signal design, the *effective green signal time* (g_1) for one of the phases can be determined using GA, while the *effective green signal time* (g_2) for the other phase can be computed by subtracting the cycle time (C) of 50 seconds as considered in this study.

X. METHODOLOGY FLOW DIAGRAM

The important steps involved in the determination of the optimal green signal timings for an isolated signal are provided **Fig. 3**.

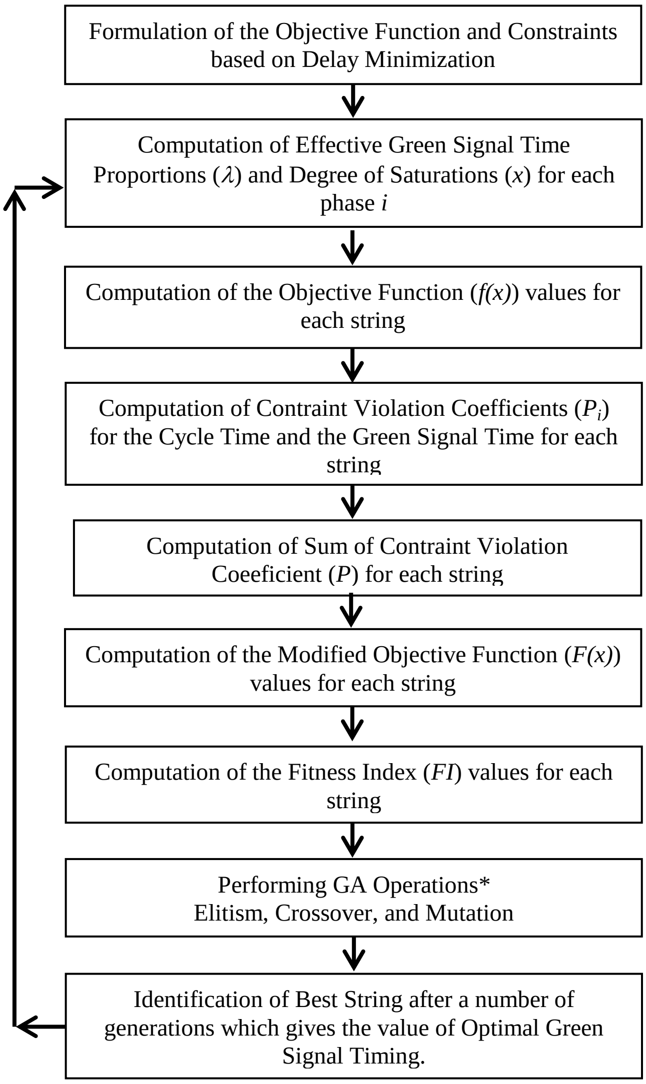

Fig. 3. Steps Involved in Determining Optimal Green Signal Timing Using GA-based Optimization Technique

Note: * GA operations:
Elitism: Selection of the best strings in the present generation with the highest Fitness Index values for the next generation
Crossover and Mutation: Selecting the remaining strings in the present generation to form new offspring's for the next generation

XI. RESULTS AND DISCUSSIONS

The experimental results obtained using GA-based approach are provided in Table-III and Table-IV

Table-III: Experimental Results of the GA Computations for the First Generation

Present Generatio n Strings	Green Signal Timings (s)	*f(x)* (s)	*P*	*F(x)* (s)	*FI*	Next Generation Offspring's
(1)	(2)	(3)	(4)	(5)	(6)	(7)
01110001	20	7.9	23.7	1887	1969	00011011
00111000	15	9.7	18.8	1847	2009	00100110
01111111	21	7.5	24.9	1899	1957	01001001
10101110	25	6.6	29.0	1941	1915	01010001
11111110	32	5.5	35.9	2015	1841	00100100
10111100	26	6.4	30.2	1954	1902	10001111
00011011	12	11.1	16.3	1841	2015	11110010
00101001	14	10.4	17.5	1842	2015	00010010
01010100	17	8.7	21.2	1864	1992	00011101
10000101	21	7.4	25.5	1904	1952	11111001

The column 1 in **Table-III** indicates 8-bit binary strings/chromosomes randomly assigned by the GA to represent the sample space for the effective green signal timing lying between the lower and upper g_{min} and g_{max} values of 10s and 32s respectively. The objective function (*f(x)*) values, sum of violation coefficient (*P*) values, the modified objective function (*F(x)*) values, and the fitness index (FI) values were computed as explained in the above sections for the present generation as tabulated in **Table-III**. Based on the fitness indices, the GA operations (elitism, crossover, and mutation) were performed to form the new offspring's for the next generation as shown in column 7 of **Table-III**.

Table-IV: Experimental Results of the GA Computations for the Final Generation

Final Generation Strings	Green Signal Timings (s)	*f(x)* (s)	*P*	*F(x)* (s)	*FI*
(1)	(2)	(3)	(4)	(5)	(6)
11101000	24	6.83	28.2	1932	1932
11101000	24	6.83	28.2	1932	1932

11101000	24	6.83	28.2	1932	1932
11101000	24	6.83	28.2	1932	1932
11101000	24	6.83	28.2	1932	1932
11101000	24	6.83	28.2	1932	1932
11101000	24	6.83	28.2	1932	1932
11101000	24	6.83	28.2	1932	1932
11101000	24	6.83	28.2	1932	1932
11101000	24	6.83	28.2	1932	1932

The process was continued iteratively for successive generations until the best string with the highest fitness index can be identified, based on which the optimal green signal time can be determined. In **Table-IV** it can be seen that the values of all the strings are same, representing the convergence of green signal timing to a global optima at around 24 seconds.

The optimal green signal timings determined for the GA-based optimization technique are provided in **Table-V** indicates that the values agree to a large extent with the optimal green signal timings computed using the conventional Webster's method [23].

Table-V: Optimal Green Signal Timings Determined Using the GA-based Optimization Technique

Phases	Green Signal Timings Computed Based on the Conventional Method (s)
North-South (Phase 1)	24
East-West (Phase 2)	18

XII. CONCLUSION

The results obtained from the GA-based optimization technique indicates better accuracy in the computation of optimal green signal timings for a two-phase isolated traffic signal. This computed optimal green signal timing impact on reducing the traffic delays through the junction. Thus, the GA-based evolutionary optimization technique is effective in the design of traffic signals. Further studies showed that the developed GA is capable of handling over-saturated traffic flow conditions in addition to the under-saturated traffic flow conditions in the design of an isolated traffic signal, whereas Webster's method is capable of handling only for under-saturated traffic flow conditions.

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