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Study of Full Controlled Green Time Roundabouts – An Intelligent Approach

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ABSTRACT

When roundabouts face congestion problems, the transition to signalised roundabouts is considered a solution to the problem. The majority of studies have concentrated on how to calculate the optimal cycle length and signal timing to minimise congestion at roundabouts. To date, intelligence algorithms with multi-objectives such as queue length, number of stops, delay time, capacity and so on are widely used for calculating signal timing. Although roundabout congestion can be generated by the weaving zone reducing roundabout capacity, there have been minimal studies which take into account the density in the weaving zone. This study proposed a hybrid gravitational search algorithm – ABFO random forest regression with the following objectives: density, delay time and capacity to find the optimal cycle length and green time in each phase of Changwon city hall roundabout in South Korea as a case study. The optimal cycle length and green time were calculated in MATLAB and microscopic simulation VISSIM sought the effectiveness of a signalised roundabout. The result of the analysis demonstrated that signalised roundabouts with 102 seconds cycle length (phase 1 – 65 seconds of green time and phase 2 – 37 seconds of green time) can reduce density by 46.1%, delays by 32.8% and increase roundabout capacity by 14.8%.

KEYWORDS

signalised roundabout; green time; optimisation; VISSIM; hybrid GSA-ABFO algorithm.

1. INTRODUCTION

1.1 Background

Traffic congestion, caused by the increased use of automobiles and limited land space, generating unnecessary time wasting and pollutant emissions from the use of fossil fuels has become a serious social problem all over the world. Solving or minimising traffic congestion is a challenging task for traffic engineers and scholars, particularly at intersections. Three types of intersections are signalised intersections, roundabouts and stop/give-way intersections, which are used widely in the world. Increasingly, signalised intersections are being replaced by roundabouts, modern versions of which were introduced in the UK in the 1960s [1]. This trend is increasing because of their advantages which are derived from the operational principle provided by their unique feature which is a central island, and have three main benefits, i.e. safety enhancement, decreased pollutant emission and increased capacity [2].

Modern roundabouts have become more compact and circulating vehicles have priority, however, many countries still use larger roundabouts as intersection control mechanisms. This is because roundabouts already exist in that place and it is difficult to change the design due to the geometric features and conditions. Moreover, roundabouts are frequently city landmarks and they are sometimes necessary for dealing with complex traffic movements composed of more than four approaches.

Roundabouts, however, also face congestion problems. Certain traffic conditions such as demand and unbalanced traffic flows at roundabouts may reduce the gap between circulating vehicles, so entering vehicles have difficulty obtaining enough gap time to enter the roundabouts [3]. Therefore, signalised roundabouts have been suggested as a countermeasure. In the roundabout design stage, signals are not generally considered and are usually only added later due to operational inefficiency [4]. Signalised roundabouts are controlled by traffic signals and can be managed based on traffic flow, signal operation time and approach control, as summarised in *Table 1* [5]. In general, indirect/part-time/partial control using a metering system can be used to shift from unbalanced traffic flows to balanced traffic flows [6]. If roundabouts are under saturation flow, direct/full controlled roundabouts are preferred to smooth vehicle movements [7].

Table 1 – Example of table caption

Classification	Control type	Description
Traffic flow control	Direct control	Entering traffic flow and circulatory traffic flows are controlled by signals
	Indirect control	Only entering traffic flows are controlled by signals
Operation time	Full-time control	Signal is operated for 24 hours
	Part-time control	Signal is activated by time of day or by detectors
Number of approaches controlled	Full control	All approaches are controlled by signals
	Partial control	Approaches are controlled by signals while the remaining approaches operate under give-way control

In recent years, several studies have attempted to maximise roundabout capacity through design changes or by installing traffic signals [8–10]. In addition, many traffic signal control algorithms have been studied. The majority of signalised roundabout studies, however, have focused on performance evaluation using a metering system. In this case, delay time, queue length or the number of stops on only one or two major approaches will be considered and analysed using traffic simulation tools, namely VISSIM, AIMSUN, Paramics and so on. Furthermore, when it comes to direct controlled roundabouts, how to minimise or reduce congestion for left-turning vehicles in the circulating lanes is the main task. Also, a variety of intelligent algorithms including particle swarm optimisation, fuzzy, genetic algorithm or neural networks can be applied to calculate and provide the optimal cycle length and phase durations for roundabouts. Despite of an increase in signalised roundabout studies, few have attempted to address the issues of density minimisation in the weaving area and questions related to cycle length and phase durations [11, 12].

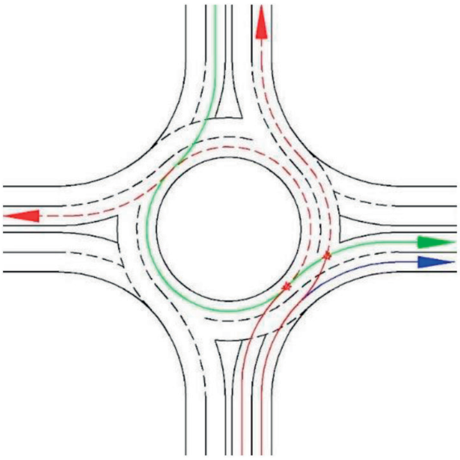
This study, therefore, selected a direct and full control method and proposed a hybrid gravitational search algorithm – random forest regression algorithm for the calculation of cycle length and phase durations to minimise vehicle conflict in the weaving area on circulation lanes and maximise roundabout capacity. The optimal signal timing will be calculated by the proposed model based on MATLAB and the signal timing will then be validated by the microscopic simulation software VISSIM, which is widely used in micro-level traffic engineering studies. Real-life data (directional traffic volumes on each approach) collected by detectors were used for modelling based on the Changwon city hall roundabout, which is a non-signalised roundabout in South Korea. Finally, the performance criteria between a normal roundabout and a signalised roundabout will be compared.

1.2 Congestion problems at roundabouts

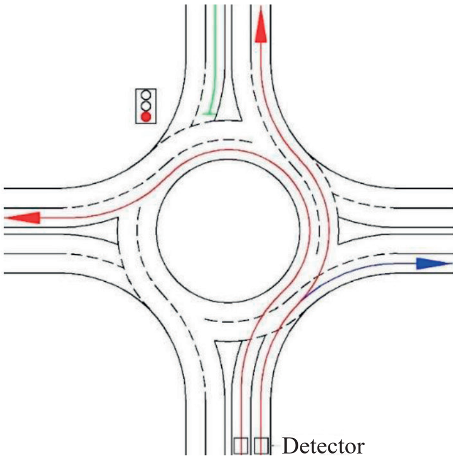
Roundabouts are operated by rules that require entering vehicles to give way to circulating vehicles that may experience congestion issues under several patterns as illustrated in *Figures 1–3*. There are three colours and two different types of lines representing basic vehicle movements at roundabouts. For example, a solid line in red shows vehicle movements without problems, but a dashed line in red indicates movements that possibly can be blocked by vehicle movements in green, while the blue line indicates only right-turn movements with no conflict.

Figure 1a presents the delays on the south approach in red through unbalanced traffic flows from the north to the east in green. In this case, metering roundabout where a traffic signal is installed on the north approach and queue detectors are located on the south approach may be a solution. When the vehicles on the south approach stay on the detectors for pre-scheduled time, the signal on the north approach is changed to red (see *Figure 1b*). As a result, vehicles have a big enough gap on the dominant (south) approach and delays will be eliminated.

Thus, studies on the investigation of a proper detector location are current and the main task is the application of metering.

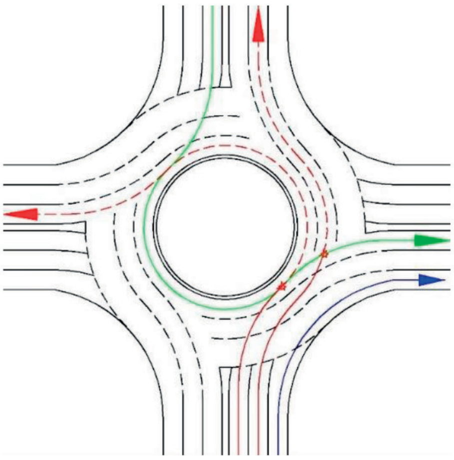


a) Congestion by unbalanced traffic

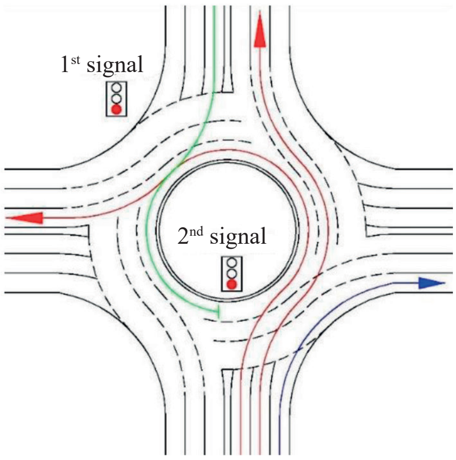


b) Solution: metering system

Figure 1 – Possible congestion at compact roundabouts by unbalanced traffic

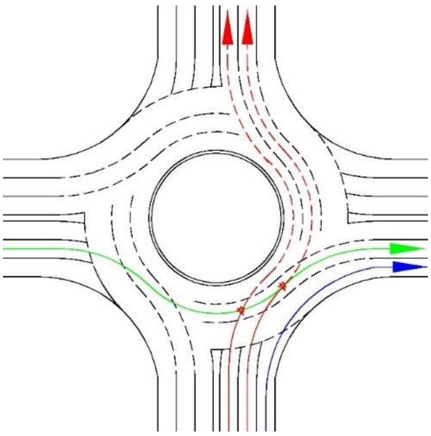


a) Congestion by left-turn traffic

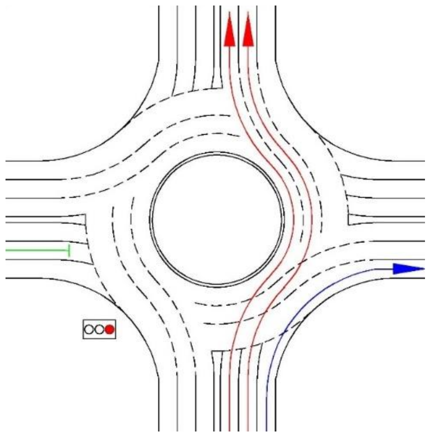


b) Solution: two-stop signal scheme

Figure 2 – Possible congestion at large roundabouts by left-turn traffic



a) Congestion by two straight vehicle movements from adjacent approaches



b) Solution: indirect control

Figure 3 – Possible congestion at large roundabouts by straight traffic

Another congestion pattern caused by left-turning movement on the circulating lanes at multi-lane roundabouts is illustrated in *Figure 2a* and vehicle movements from the south approach in red can be blocked by left-turning vehicles from the north approach in green. In general, this pattern might be occurring at a large roundabout and two-stop line control can be suggested as a countermeasure. In this case, two traffic signals are necessary: one controls approaching traffic and the other one controls circulating traffic as depicted in *Figure 2b*. When the second signal is red, the left-turning vehicles will stop and vehicles from the south approach can obtain enough gap time for smooth enter. Thus, an appropriate phase scheme and signal timing are required.

The last reason for roundabout congestion is the conflict between two straight vehicle movements from adjacent approaches in the weaving area at multi-lane roundabouts as shown in *Figure 3a*. Mainly vehicles from south to north in red and from west to east in green can conflict the circulating lanes in the weaving zone. Thus, the congestion in the weaving zone may block vehicle movements from other approaches resulting in a decrease in capacity. Normally, this problem can occur at large roundabouts because the large central island has a long weaving area. For this congestion pattern, few studies have attempted to address the issue and full control may minimise vehicle delays in the weaving area with a decent signal timing plan as presented in *Figure 3b*.

2. LITERATURE REVIEW

As mentioned earlier, many studies on signalised roundabouts have been conducted by scholars and engineers to date. In terms of signalised roundabout studies, they can be divided roughly into three parts and active research is ongoing as follows: first, a comparative study between normal roundabouts and signalised roundabouts using traffic simulation software. Second, a study for the application of a metering system to reduce delays caused by unbalanced traffic conditions on one or two approaches. Lastly, a signalised roundabout optimisation study through calculating and providing the optimal traffic signal timing based on traffic theory to solve the congestion on the approaching and circulating lanes.

In [13], the application of a metering system was studied and SIDRA software was used for the analysis of metered roundabouts. Vlahos also used SIDRA software for signalised roundabouts evaluation with different entry volumes [14]. In [15–17], delay time, queuing length and capacity were compared between normal and signalised roundabouts using Paramics, AIMSUN and SIDRA software. In [18], a new method for evaluating signalised roundabouts with two signals and one detector was proposed using 4-nodes intersections in SIDRA. These studies found that a metering system can increase roundabout capacity and that metered roundabouts outperform the management of vehicle movements on the main approach under unbalanced traffic flow conditions. Comparative studies of performance effectiveness, however, mainly deal with the situation when a normal roundabout converts to a signalised roundabout, relying on software to analyse capacity, delays, travel time and so on, and there has been no study of traffic signal timing calculation.

In terms of metered roundabout studies, Akçelik [6] studied how cycle length can affect delays and found that a shorter cycle length could lead to better performance compared with a longer cycle length for roundabouts with a metering system. The author [6] recommended that cycle lengths of 75 seconds, 86 seconds and 114 seconds are suitable for the entire entering volume of 1,500 vph, 1,800 vph and 2,100 vph, respectively. Some other researchers [18–23] have conducted queuing length estimation studies, which is related to signal timing plan, for one or two main approaches. A study of the estimation of queuing length was conducted by Flannery [18] and the M/G/1 model was utilised based on a single-lane roundabout. In the study, critical gap, follow-up headway and queue spacing were investigated using SIDRA software. Another researcher Martin-Gasulla [20] used VISSIM software to calculate the appropriate cycle length on a large roundabout, while Hummer et al. [21] used VISSIM to compare metered and unmetered roundabouts to reduce delays. In [22], formulated queuing length equations were applied to find the best detector locations with six major parameters affecting queuing length on each approach. The author [23] further studied the estimation of queuing length at metered roundabouts based on an adaptive neuro-fuzzy inference system to select the optimal detector distance. Although many studies have tried to seek the optimal cycle length and phase durations following real-time volumes, it is very difficult to set a proper signal timing plan. Thus, the majority of studies have concentrated on a fully actuated operation with detectors and traffic signals connected for solving congestions on one or two approaches only, and it has a valuable benefit-cost ratio due to easy operation and a low installation cost [13]. However, the drawback of these studies is that the analysis of roundabout performance only focused on the dominant approach where mostly delays can occur and detectors need to be installed (*Figure 1b*). Thus, many studies related to the application of metering systems found that a shorter cycle length can help roundabout performance [6, 20].

Concerning signal timing studies, several researchers tried to enhance roundabout capacity by applying a signal timing plan and adjusting the phase sequence [24–30]. In [24, 25], direct and full control method was tested and a two-stop line roundabout was proposed to help left-turning vehicles. The research calculated the best green time for straight traffic on each approach at the first stop line and vehicles turning left on the circulating lanes at the second stop line [25]. From the research, it can be found that cycle length and island size could affect the flow of left-turning vehicles on the circulating lanes. In [26], a dual-ring scheme and two-stop line for left-turning vehicles were taken into account for the elimination of the conflict points at a roundabout. These studies concluded that a shorter cycle length is necessary to decrease vehicle delay and queue at roundabouts when the left turn ratio is lower. This is because clearance time can determine the green time for left-turn vehicles. In addition, if there is enough space before the second stop line, the vehicles turning left and vehicles going straight can have the same green time together. Also, a shorter cycle length will eliminate vehicle delays at the second stop line on the circulating lanes. Another study by Bie et al. [27] focused on signal timing calculation at roundabouts based on two delay models and two queue length models under two-phase schemes. This study selected indirect and full-time control and also tried to reduce delay time and queue length on the circulating lanes incurred by left-turning vehicles only [27]. In [28], the optimal stop-line setback distance was conducted with a three-phase scheme to reduce the queues for right-turning vehicles. An adaptive control algorithm was used with the concepts of the length of the waiting area and rule-based signal control logic, and a case study was demonstrated by VISSIM. The authors concluded that the stop-line setback with a proper signal timing plan can reduce vehicle delays by 18.3% [28]. However, the stop-line setback method was recommended for one or two approaches because it is ineffective for all approaches. Another study performed by Murat et al. [29] calculated the optimal cycle length for the signalised roundabout in Denizli, Turkey. This study was performed based on the relationship between the space on the circulating lanes of central island and the left-turning volume. In addition, the average delay time was selected as performance criteria. In [30], the cycle length and effective green time were adjusted by GA for reducing the average delay time and it can be concluded that a longer green phase duration can decrease roundabout congestion. This is because the study only tested the situation when the total entering volume was less than 2,000 vph at the four-leg with a multi-lane roundabout. Therefore, different from the previous studies on metering roundabouts and two-stop control roundabouts, it is concluded that a longer cycle is more effective.

There have been several studies related to signal timing research which found that signalised roundabouts outperform normal roundabouts under special conditions. However, the majority of studies concentrated on how to reduce queues, delays, number of stops and increase capacity according to signal phase time changes. There have been minimal studies considering the minimisation of density in the weaving zone affecting roundabout capacity, which is a key factor in straight movements from two adjacent approaches. The above-mentioned studies were conducted on the condition that the total entering volume maintained less than 3,000 vph. There is no study reported according to the author's knowledge with the total entering volume greater than 5,000 vph at roundabouts.

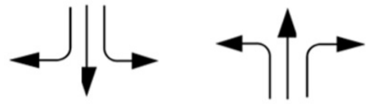
3. RESEARCH METHODOLOGY

3.1 Design of phase scheme and weaving area

This study aims to minimise the number of conflicting vehicles in the weaving zone for roundabout capacity enhancement. Thus, indirect (only entering traffic is controlled by traffic signals), part-time (traffic signals operate only during peak times) and full control (all approaches are controlled) operation methods were selected (*Table 1*). During off-peak times the roundabout will follow normal roundabout rules.

At signalised roundabouts, the design of a phase diagram is an essential step. For 4-leg intersections, a variety of signal phase schemes can be implemented, but this study adopts a two-phase for 4-leg multi-lane roundabout to eliminate conflicting vehicles in the weaving zone as shown in *Table 2*. This is because congestions in the weaving area can occur by mainly straight movements between adjacent approaches, thus a two-phase scheme can effectively separate the movements.

Table 2 – Design of phase scheme

Phase 1	Phase 2
Vehicles from south and north can enter the roundabout	Vehicles from east and west can enter the roundabout
	

In general, traffic from north to east and west to east try to exit through the east exit approach whereas entering traffic from the south tends to move to the north (straight) and west (left-turn) exit approaches. Thus, the weaving area can be defined as an area where circulating traffic and entering traffic meet together and weaving zones are as presented in *Figure 4*.

The weaving zones can be explained as an example of zone 1, vehicles from approach 4 to approach 3 and vehicles from approach 1 to approach 2 do not conflict with each other, therefore these are non-weaving volumes. However, there is a conflict between vehicles from approach 4 to approach 3 and vehicles from approach 1 to approach 3 and 4 in the weaving zone, therefore these are weaving volumes. In addition, vehicles from approaches 3 and 4 to approach 2 also should be regarded as weaving volumes as opposed to vehicles from approach 4 to approach 3. These non-weaving and weaving volumes are also presented in *Figure 2*.

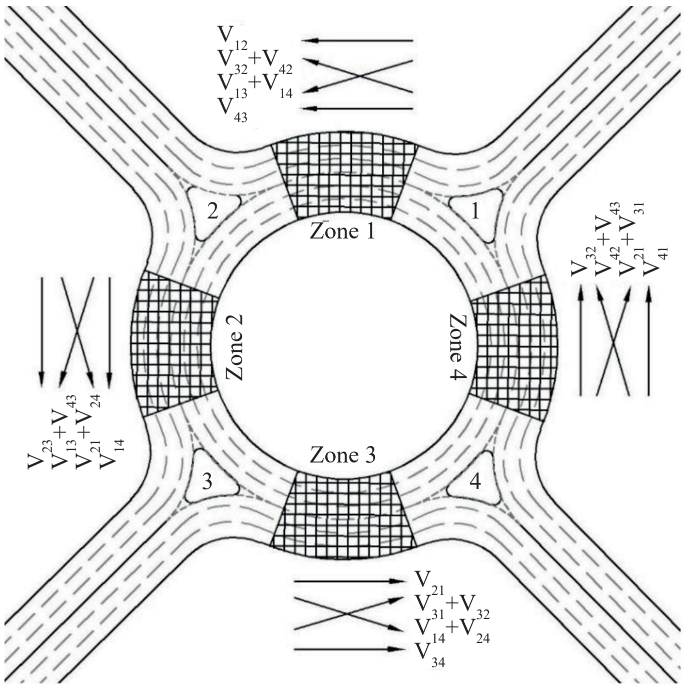


Figure 4 – Weaving section at a roundabout

During phase 1, vehicles from approaches 1 and 3 can be blocked, so weaving volumes from approach 1 to approaches 3 and 4 and non-weaving volumes from approach 1 to approach 2 do not need to be considered. In the case of phase 2, non-weaving volume from approach 4 to approach 3 also cannot enter the roundabout. These concepts can be applied to calculate density in each zone following phase changes.

3.2 Objectives and constraint

This study focuses on the roundabout capacity enhancement by minimising density in the weaving zone and delays on each approach by providing the optimal cycle length and phase time. Thus, density, delays and capacity can be objectives for calculating the signal timing and hybrid gravitational search algorithm – random forest regression is used for optimising the roundabout performance.

In addition, to reflect roundabout geometry, one-sided weaving segments will be applied for the calculation of density, which can be expressed as [31]

$$D_i = \lambda_i \sum_1^j D_j \tag{1}$$

where D_i is the average density of roundabout in phase *i* (pc/km/ln) and λ_i is the green ratio of phase *i*. The density of each zone will be calculated following signal phase changes.

$$D_j = \frac{\frac{V}{N}}{S} \tag{2}$$

where D_j is the density of zone *j* (pc/km/ln), *N* is the number of lanes within the weaving section, *S* is the average speed of all vehicles within the weaving section and *V* is total demand flow rate in the weaving section (pc/h).

For the vehicle delay model at intersections, the Webster model is most widely used by traffic engineers and designers [32] and the model is described in *Equation 3*

$$d_i = \frac{(C-\lambda_i)^2}{2(1-\lambda_i X)} + \frac{X^2}{2v(1-X)} - 0.65\left(\frac{C}{v^2}\right)^{\frac{1}{3}} X^{(2+5\lambda)} \tag{3}$$

where d_i is average vehicle delay (s) in phase *i*, *C* is cycle length (s), *X* is the volume-to-capacity ratio and *v* is arriving volume (veh/h).

The capacity of the intersection is the maximum flow ratio of approach in each phase as expressed in *Equation 4*

$$Q = \sum_1^n Q_i \tag{4}$$

where *Q* is the total traffic capacity at the intersection.

$$Q = S_i \lambda_i \tag{5}$$

where Q_i is capacity in phase *i* and S_i is the traffic saturation flow rate in phase *i*.

To reflect the actual traffic environment and get more accurate results, several constraints (i.e. cycle length, effective green time) need to be considered. If the cycle length is too short, not enough vehicles on the approach can pass through the intersection which is leading to delays. Whereas, if the cycle is too long, other approaches will possibly face delays. Thus, a decent cycle length needs to be calculated and provided and the constraint of cycle length is presented in *Equation 6*. C_{min} can be 30 seconds and C_{max} will be 160 seconds.

$$C_{min} \le C \le C_{max} \tag{6}$$

where C_{min} is the minimum cycle length (s), *C* is the cycle length (s) and C_{max} is the maximum cycle length (s).

Another constraint of cycle length is that the total cycle length should be the same as the sum of the green time and the lost time in each phase. It can be written as *Equation 7*

$$\sum_i^n (g_i + L_i) = C \tag{7}$$

where g_i is the effective green time in phase *i* (s), and L_i is the total loss time in phase *i* (start-up lost time + clearance lost time).

Therefore, the objective function to minimise density and delay and maximize capacity can be expressed in *Equation 8*

$$f(x) = \min\left(a_1 \frac{D_i}{D_{max}} + a_2 \frac{d_i}{d_{max}} + a_3 \left(1 - \frac{Q_i}{Q_{max}}\right)\right) \tag{8}$$

where multi-objective weight factor a_1= 0.4, a_2= 0.3, a_3 = 0.3.

3.3 Proposed algorithm

Bacterial foraging algorithm

The basic principle of this algorithm is to complete the information exchange according to the interaction between the cilia of Escherichia coli itself and the bacteria and make the bacteria up to the higher nutrient concentration through chemotaxis, replication and migration operations to find the optimal solution of the parameters. The bacterial foraging (BFO) algorithm has been widely used in engineering practice because of its simple principle, easy programming, fast convergence and strong searchability. Studies have shown that the standard BFO algorithm uses a fixed step size and random flip direction, which reduces the directionality of the algorithm optimisation and can quickly find the optimal solution [33]. After several steps of chemotaxis and replication, the food where the bacteria are located is partially consumed, and the bacteria can choose to continue being in place or find a new food source. The bacterial foraging algorithm designs a migration rate. For each bacterium, a random number between 0 and 1 is generated. When the random number is less than the preset migration probability, the bacterium will be randomly migrated to other locations. Otherwise, the bacteria continue to the next operation with the current position. To prevent the population from losing the optimal solution due to the migration operation, each randomly initialised parameter can be compared with the objective function value of the original parameter before the migration position replaces the original position, and only the bacteria with better performance will proceed to the next iteration [34].

Gravitational search algorithm

Gravitational search algorithm (GSA) is a heuristic algorithm inspired by Newton's basic law of gravity, which states that "the attraction between each individual in the universe is proportional to the product of its mass and inversely proportional to the square of the distance" [35]. In GSA, individuals are considered objects that are attracted to each other by gravity. Each individual consists of position, mass, and active and passive gravitational mass and can be defined as [36]:

$$y_i = (y_i^1, y_i^2, ..., y_i^d, ..., y_i^n \tag{9}$$

where the position of the i individual in the d-th dimension is in the y_i^n dimensional search space; in a set of N individuals, the position of the i-th individual (i = 1, 2, ..., N).

The gravitational force acting on the i-th individual by the j-th individual at the t-th iteration is defined as:

$$F_{ij}^d(t) = G(t)\frac{M_{pi}(t) \cdot M_{aj}(t)}{R_{ij} + \varepsilon}(y_j^d(t) - y_i^d(t)) \tag{10}$$

where M_{aj} is active gravitational mass associated with individual j; M_{pi} is passive gravitational mass associated with individual i; ε is a very small constant; R_{ij} is the Euclidean between two individuals i and j distance.

The velocity and position update equations for the i-th individual in t iterations in the d-th dimension are given below:

$$v_i^d(t+1) = rand_i \cdot v_i^d(t) + acc_i^d(t) \tag{11}$$

$$y_i^d(t+1) = y_i^d(t) + v_i^d(t+1) \tag{12}$$

where $v_i^d(t)$, $v_i^d(t+1)$ and $y_i^d(t)$, $y_i^d(t+1)$ are the velocity and position of individual y_i in d-dimension at time t and t+1.

Hybrid GSA-ABFO algorithm

In this study, a combination of the optimisation strategy of the gravitational search algorithm and adaptive bacterial foraging algorithm (GSA-ABFO) is proposed to find the optimal cycle length and green time in each phase. Using the GSA-ABFO algorithm, we can redefine the health degree and location evaluation method of bacteria, which ensures the random search characteristics of the algorithm. Using the random flip direction of bacteria, the learning coefficient of bacteria on the historical optimal position information is introduced, and the reinforcement learning direction is proposed in combination with the concept of global optimisation of GSA to reduce the blindness of the simple random flip method.

The reinforcement learning direction calculation is:

$$\Delta_{RL}(i) = (\theta_i - \theta_b)\theta_r R_1 \quad (13)$$

where $\Delta_{RL}(i)$ is the reinforcement learning direction of bacteria; θ_i is the current bacterial position; θ_b is the optimal bacterial position after the previous chemotaxis; θ_r is the reinforcement learning coefficient; R_1 is a random number. The chemotaxis direction $\Delta M(i)$ of bacteria is as follows:

$$\Delta_M(i) = \Delta(i) - \Delta_{RL}(i) \quad (14)$$

We can identify the real-time record and update the position information of the optimal individual in the group and adjust the bacterial swimming step length according to the positional relationship between the current individual and the optimal individual in the group to improve the optimisation accuracy of the algorithm. The bacterial location is updated as

$$\theta(i,j+1,k,l) = \theta(i,j,k,l) + \frac{C(i)\Delta_M(i)}{\Delta_M^T(i)\Delta_M(i)} \quad (15)$$

where $\theta(i,j,k,l)$ represents the location coordinates of the bacteria, and j, k and l represent the chemotaxis, replication and migration times where the bacteria are currently located, respectively; $C(i)$ is the swimming step length of bacteria i, and its value will be appropriately changed according to the actual situation.

To improve the convergence speed, when updating the fitness of bacteria, the influencing factors between bacteria are added and determined according to the positional relationship between bacteria and other bacteria, that is,

$$J_{cc}^{i,b} = -h_a e^{-w_a D_{1,b}^2} + h_r e^{-w_r D_{1,b}^2} \quad (16)$$

where $J_{cc}^{i,b}$ are the influencing factors of the current bacteria and other bacteria; h_a, w_a, h_r and w_r is the number of attractants, the release rate of attractants, the number of repellants and the release rate of repellants, reflecting the information exchange between bacteria.

After each chemotaxis cycle, the standard ABFO takes the sum of the previous fitness of bacteria as the bacterial activity (health degree) and based on this, the replication and elimination of bacteria are carried out. It is easy to cover up and lose the historical optimum of bacteria information if the algorithm does not converge fast enough.

To improve the speed of the algorithm, the optimal historical fitness of bacteria is directly used as the health degree of bacteria and the bacteria are sorted according to the health degree, and the bacteria are copied and eliminated to keep the total number of bacteria unchanged.

$$J_{health}^i = \min(J(i,1:N_c,k,l)) \quad (17)$$

where the maximum number of bacterial chemotaxis, replication and migration operations are N_c, N_{re}, N_{ed}, respectively, and $J(i,1{:}N_c,k,l)$ is the fitness of the i-th bacterium, and its size is used to evaluate the pros and cons of candidate solutions.

The process of the traffic signal timing optimisation model is described in *Figure 5*. The proposed scheme for optimising the density, delay time and capacity for the Changwon city hall roundabout is based on hybrid GSA-ABFO algorithm.

The main steps of the algorithm are as follows.

1) Parameter initialization. Set parameters such as S, p, N_c, N_{ed}, N_{re}, etc.; initialize the bacterial position and calculate the fitness to find the initial optimal position.
2) When l=1: N_{ed}, go to step 3; when k=1: N_{re}, go to step 4; when j=1: N_c, go to step 5.
3) Calculate the initial fitness of the population. For different bacteria, calculate the final fitness of the superimposed influence factors:

$$J_{ca}(i,j,k,l) = J(i,j,k,l) + J_{cc}^{i,b}(i,j,k,l) \quad (18)$$

4) Calculate the chemotaxis direction and swimming step length of bacteria.
5) Update the bacterial position according to *Equation 15* and calculate the fitness $J_{ca}(i,j,k,l)$ under the new position.

6) Determine whether the fitness has been improved in the new position, if so, continue to mass forward in the same direction to update the position and fitness; if the fitness is worse or reaches the set maximum number of swimming steps, the bacteria stop continuing to mass, retain the location information of the current bacteria and then enter the chemotaxis of the next bacteria.
7) All bacterial chemotaxis operations are completed in one round, the bacterial information of the optimal position is judged and the chemotaxis cycle ends.
8) For each bacterium in the population, take the optimal fitness value in the chemotaxis process as the health degree of the bacterium, sort by health degree, half of the bacteria with better fitness, and eliminate the bacteria with poor fitness. The operation is over and the migration operation is entered.
9) For each bacterium, a random number is generated between 0 and 1, and the random number is used to compare with a specific probability (usually 0.25). The bacterium migrates when the random number is lower; otherwise, it remains in position.

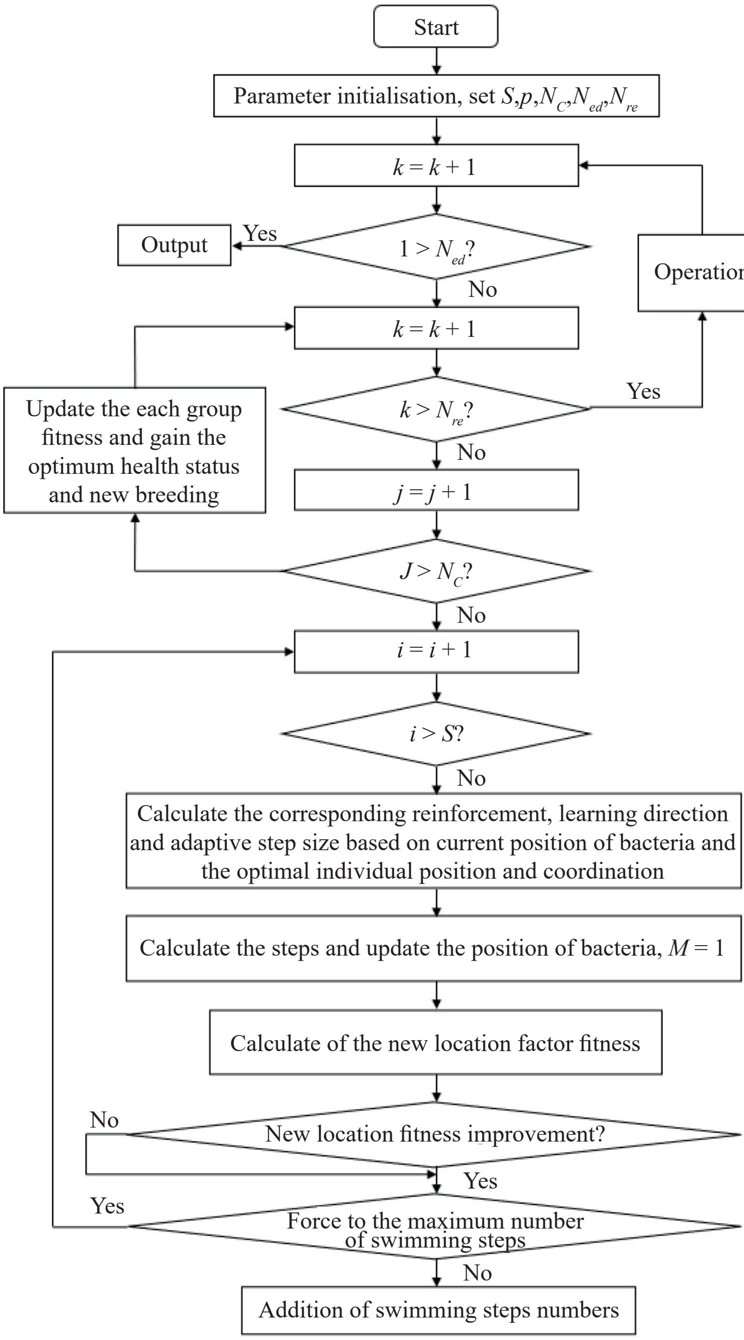


Figure 5 – The process of traffic signal optimisation using the hybrid GSA-ABFO algorithm

4. DATA COLLECTION

As mentioned earlier, to find the optimal cycle length and phase time, Changwon city hall roundabout was selected as the study site. In front of Changwon city hall, there is a large roundabout (diameter is 200 meters), and it is a 4-leg multi-lane roundabout, currently operated as a normal roundabout as shown in *Figure 6a*. The geometric features of the roundabout are quite complicated. Approach 1 (East-North) and 4 (East-South) have three entering lanes whereas approaches 2 (West-North) and 3 (West-South) have four entering lanes. However, approach 1 has four lanes for exiting while the other approaches have five exit lanes. Moreover, six lanes are circulating between approaches 1 and 2 and there are five circulating lanes on the others, and approaches 2 and 3 both have a slip lane for turning right.

a) Approach number *b) Traffic on the circulating lanes*

Figure 6 – Changwon city hall roundabout

Volume data were collected on 15 July 2020. A feature of this roundabout is that in the afternoon peak approximately 5,500 vehicles pass through the roundabout and every minute the arriving volume is changing as presented in *Figure 7*. Approaches 2 and 4 have almost double volumes compared with the other two approaches.

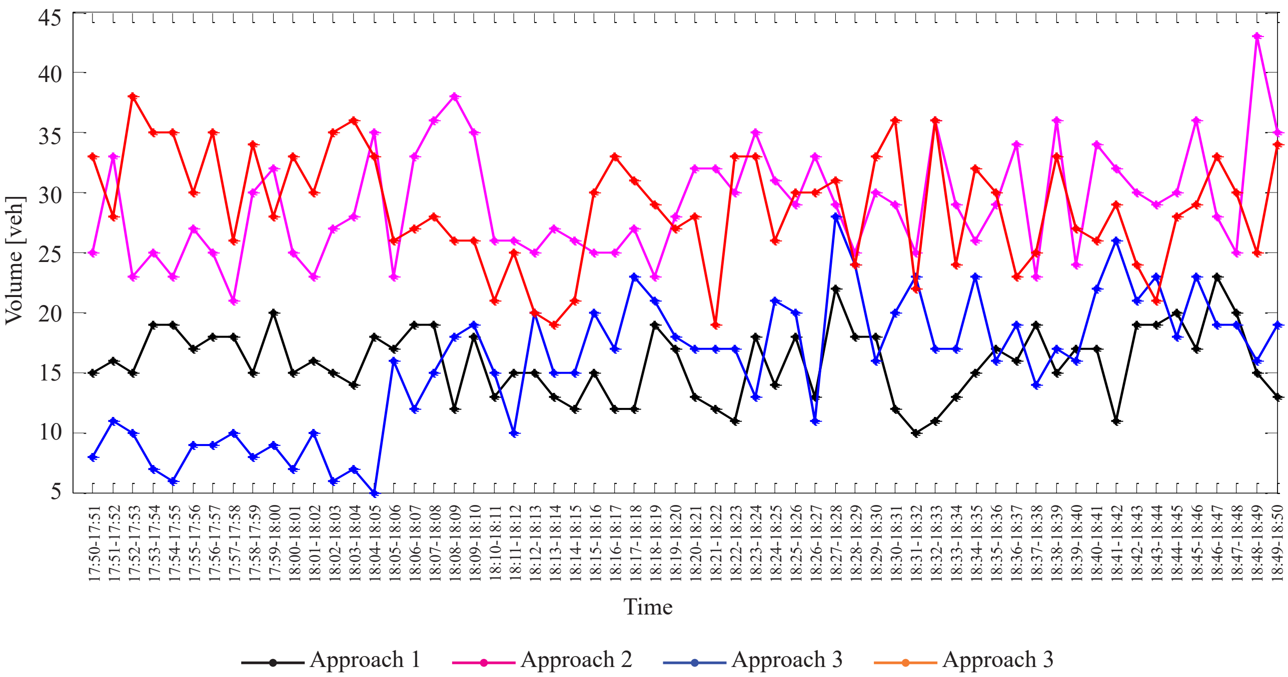


Figure 7 – Traffic volume in every minute in the afternoon peak

The problem with this roundabout is the conflict between two straight movements because from approach 2 to approach 4 and from approach 4 to approach 2 there are more than 1,100 vph blocking vehicle movements from approaches 1 and 3, respectively. Also, due to the conflict, the vehicles moving straight from the two approaches cannot exit properly from the roundabout, in particular at approach 1 where the delay time is longer. Thus, congestion can be generated on the circulating lanes resulting in a reduction of roundabout capacity as shown in *Figure 6b*. In addition, 52.5 seconds, 10.5 seconds, 22.0 seconds and 35.0 seconds of average delay time during peak hour were observed on approaches 1, 2, 3 and 4, respectively. This average delay time will be used for VISSIM calibration.

5. ANALYSIS AND RESULTS

5.1 Cycle length and phase duration study

The proposed algorithm attempts to find the green time for phases 1 and 2 to maximise roundabout efficiency. *Figure 8* shows the number of iterations and after 36 iterations the algorithm converges stably with 102 seconds of cycle length. Consequently, the green time for phase 1 has 65 seconds and 3 seconds of yellow time and phase 2 is composed of 37 seconds of green time and 3 seconds of yellow time for the roundabout signal timing, which optimised density, delay and capacity on Changwon city hall roundabout.

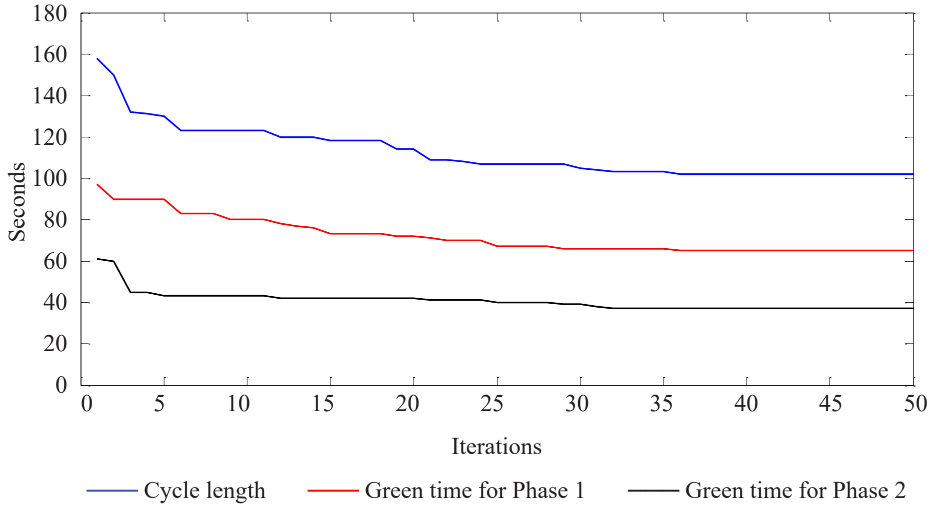


Figure 8 – Number of iterations

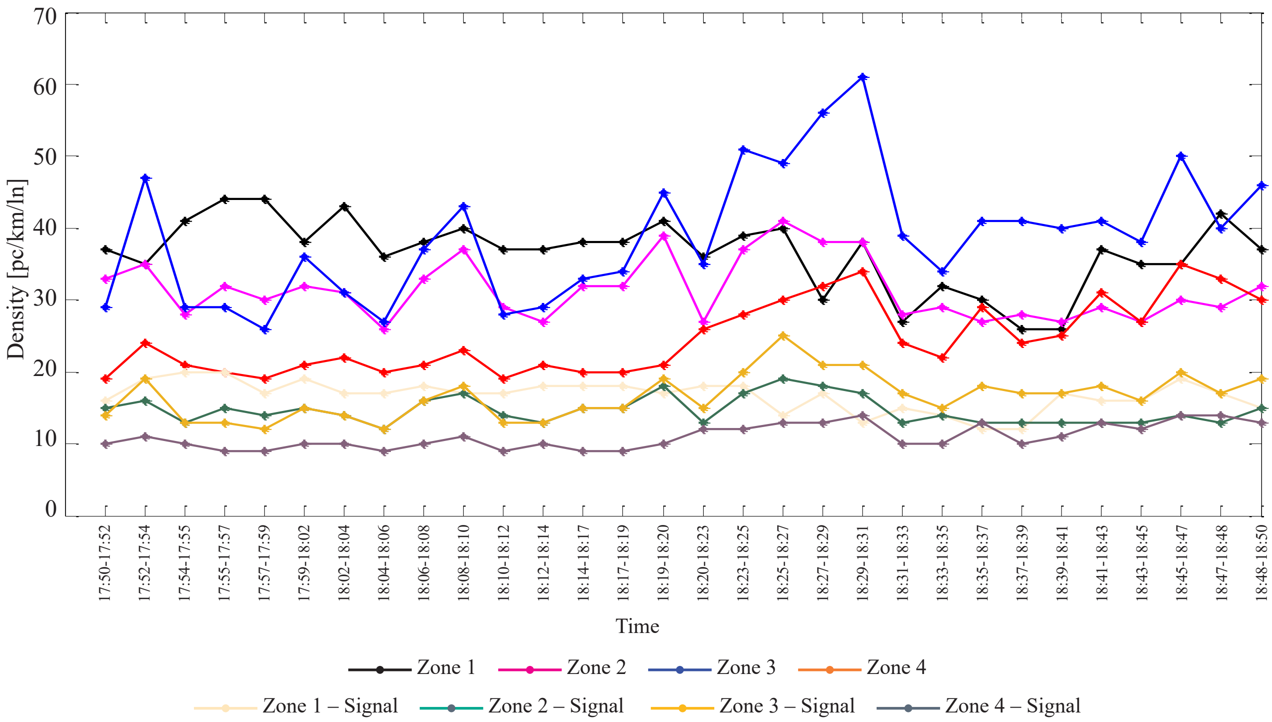


Figure 9 – Average density comparison between the normal and signalised roundabout

The density on each weaving zone is variable according to real-time traffic and it can be calculated with a cycle length for peak hour as depicted in *Figure 9*. In addition, the density on the weaving zone cannot be calculated using microscopic simulation VISSIM software, therefore the density on each zone was calculated by MATLAB software to check how much difference arose between the before and after study. Generally, the density on each weaving zone without a signal is higher than the density with a signal scheme, which is thus able to minimise the vehicle conflict between two straight movements. With normal roundabout conditions, density in zone 1, zone 2, zone 3 and zone 4 were 36.5 pc/km/ln, 31.4 pc/km/ln, 38.8 pc/km/ln and 24.7 pc/km/ln, respectively. It means the average density at Changwon city hall roundabout was 32.8 pc/km/ln. However, after the application of a two-phase signal scheme, the densities of 16.7 pc/km/ln, 14.7 pc/km/ln, 16.5 pc/km/ln and 10.9 pc/km/ln were calculated in zone 1, zone 2, zone 3 and zone 4, respectively, representing the concentration of reduced density by 46.1% or 14.7 pc/km/ln for entire zones.

5.2 Delay and capacity analysis in VISSIM

To validate the proposed model and solution algorithm for Changwon city hall roundabout signal timing optimisation, a computational experiment was conducted. Specifically, the cycle length and green time for phases 1 and 2 by MATLAB were applied to VISSIM microscopic simulation where the network of the roundabout is utilised for the experiment as shown in *Figure 10*.

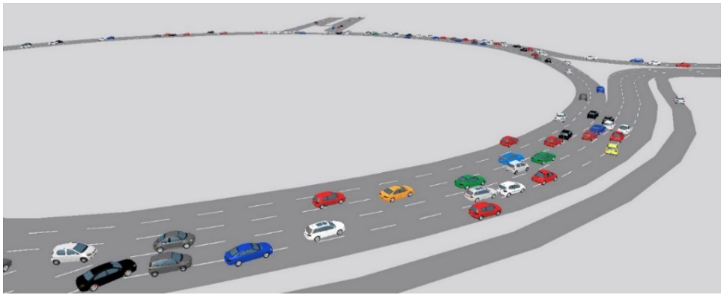


Figure 10 – Changwon city hall roundabout in VISSIM

The existing traffic circumstances, including network layout, traffic volumes and driver behaviour were represented in VISSIM. Furthermore, to match the delay time on each approach using the field data, key parameters were calibrated as summarised in *Table 3*.

Table 3 – Adjusted parameters in VISSIM

Parameters			Default value	Adjusted value
Driving behaviour parameter	Look ahead distance [m]	Minimum	0	120
		Maximum	250	500
		Number of observed vehicles	4	5
	Look back distance [m]	Minimum	0	50
		Maximum	150	155
	Wiedemann 74 car following model	Average standstill distance [m]	2	1.35
		Additive part of safety distance	3	0.25
		Multiplicative part of safety distance	3	0.35
	Lane change	Waiting time before diffusion [s]	60	50
		Minimum headway [min]	0.5	0.2
	Lateral behaviour	Desired position at free flow	Middle	Any
		Observe adjacent lane [s]	No	Yes
		Diamond shaped queuing	No	Yes
		Consider next turn	No	Yes

The delay time on each approach was compared with VISSIM results and the Geoff E. Havers statistic (GEH), which is a Chi-squared type statistic to verify the fitness of the model. This test has widely been employed in transportation engineering and modelling for model output and observation comparisons [37]. Five-minute interval statistical test results of the delay time on each approach are depicted in *Table 4*. All the GEH results are less than five and the maximum value is measured at 1.03 on approach 3, which means that model outputs fit with field data properly and are well-calibrated.

Table 4 – Results of statistical test

Time	Delay time [s]							
	Approach 1		Approach 2		Approach 3		Approach 4	
	Field	VISSIM	Field	VISSIM	Field	VISSIM	Field	VISSIM
17:50-17:55	53.1	51.8	9.2	9.8	20.6	24.8	33.6	31.8
17:55-18:00	53.7	52.4	10.3	11.6	25.6	32.1	38.6	36.4
18:00-18:05	47.2	56.4	10.2	13.5	22.7	31.1	37.4	30.4
18:05-18:10	50.1	50.3	9.7	16.8	22.3	28.4	33.2	28.5
18:10-18:15	51.1	49.4	11.5	15.7	23.8	28.6	38.3	28.9
18:15-18:20	55.4	56.2	8.3	13.4	17.5	24.6	33.7	30.2
18:20-18:25	50.9	56.5	9.8	12.6	20.6	24.8	31.1	33.6
18:25-18:30	57.2	57.2	10.8	13.6	22.4	18.3	30.4	34.5
18:30-18:35	51.6	56.5	12.5	14.8	23.1	29.4	30.5	36.7
18:35-18:40	52.4	50.7	11.6	15.8	19.2	23.5	38.7	30.8
18:40-18:45	54.1	52.1	11.5	16.9	22.4	19.6	36.5	33.5
18:45-18:50	52.2	53.8	9.8	13.8	21.8	19.8	38.7	36.8
RMSE	0.34		1.01		1.03		0.78	

Figure 11 shows the average delay time on each approach between a normal and signalised roundabout for peak hours. With 102 seconds of cycle length (green time 65 seconds for phase 1 and 37 seconds for phase 2), the average delays on each approach decreased. Specifically, the average delay was decreased on approaches 1 and 4 by 44.8% and 43.7%, respectively, by the application of signal control. In terms of the entire roundabout, the average delay time was reduced by 32.8%.

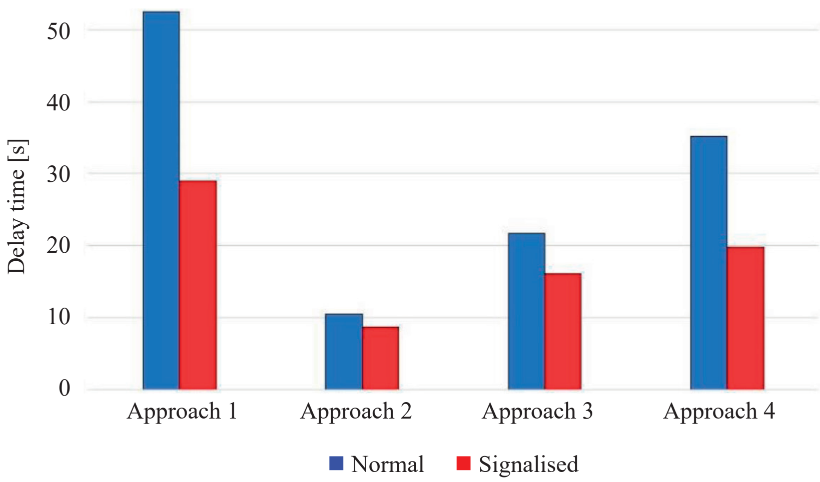


Figure 11 – Average delay comparison on each approach between the normal and signalised roundabout

Concerning capacity, the operation of the roundabout with signal enables an increase in capacity on each approach as shown in *Figure 12*. When compared with the capacity generated by the current normal roundabout, there is a decrease in capacity effectiveness of 11.3% (approach 1), 12.6% (approach 2), 20.5% (approach 3) and 12.8% (approach 4), total of 12.8% reduction in roundabout capacity.

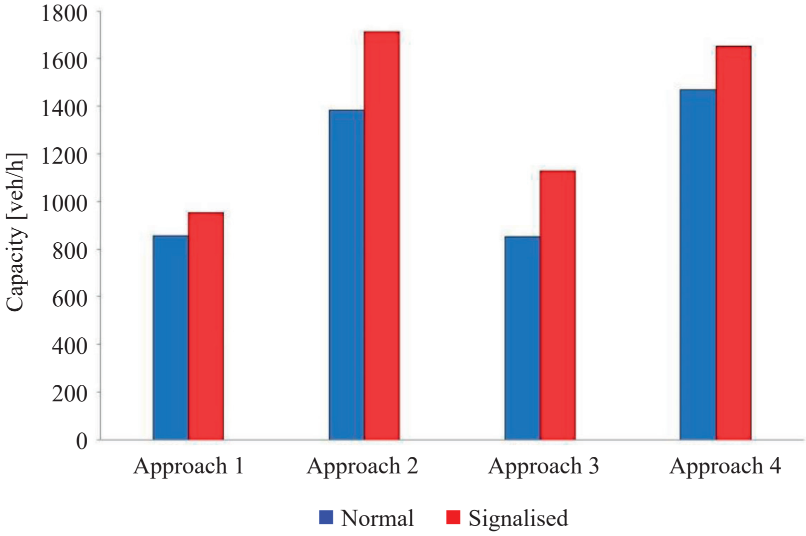


Figure 12 – Capacity comparison on each approach between the normal and signalised roundabout

The entire roundabout delay time and capacity in accordance with cycle length changes within the range of 30–160 seconds as can be seen in *Figure 13*. A shorter cycle length increases delay time, e.g. when the cycle length is 30 seconds, the roundabout has the maximum delay time (approximately 140 seconds). On the other hand, the delay time at the roundabout is minimum and the capacity is maximum when the cycle length is 105 seconds. A longer than 105 seconds cycle length results in roundabout inefficiency.

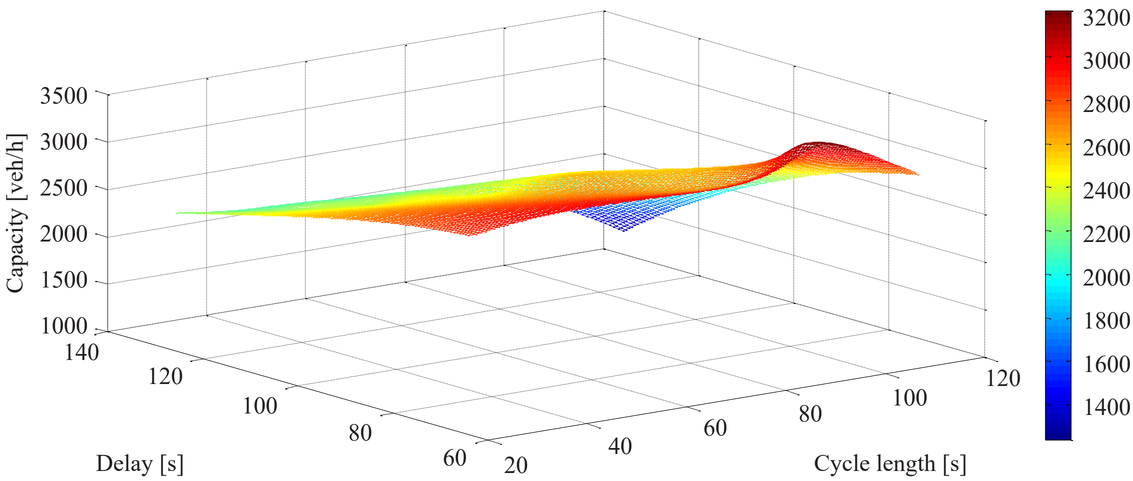


Figure 13 – Total delay and capacity following cycle length changes

6. CONCLUSION

This study attempted to introduce an intelligence algorithm to find the optimal signal timing by taking a case study on the Changwon city hall roundabout for minimising congestion in the weaving zone affecting the entire roundabout's efficiency. Hybrid gravitational search algorithm – ABFO random forest regression and two-phase signal phase schemes have been proposed. In particular, density in the weaving zone was selected as one of the objectives. To validate the proposed algorithm, the optimised signal timing was tested through the use of microscopic simulation VISSIM. Furthermore, density in the weaving zone by MATLAB and delay time and capacity by VISSIM were compared between a normal and signalised roundabout.

Through the proposed model application described in this study, the optimum cycle length was found to be 102 seconds (phase 1–65 seconds of green time and phase 2–37 seconds of green time) during the afternoon peak hour. The results from the analysis indicate that the optimised signal timing suggested by the proposed algorithm can increase the entire roundabout performance density by 46.1%, increase capacity by 14.8% and decrease delays by 32.8%. Thus, it is expected that the proposed algorithm will help and guide practitioners in determining optimal signal timing and will be a foundation study for solving congestion problems by two straight movements between adjacent approaches at roundabouts.

However, there are some limitations in this study and more case studies need to be carried out in the future based on different geometric designs and the number of lanes. In addition, the proposed algorithm needs to be compared with previous intelligence algorithms to check model accuracy.

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인공지능 기법을 바탕으로 한 회전교차로 신호시간 연구

초록
회전교차로에서 교통 혼잡 발생시, 신호 회전교차로로의 전환이 문제의 해결책으로 떠오르고 있다. 최근 신호 회전교차로에서 발생하는 혼잡을 해결하기 위해서 최적의 신호주기 및 녹색신호 시간 산정 방법에 대한 연구가 활발히 진행 중이다. 여기에 대기행렬 길이, 정지 횟수, 지체 시간, 용량 등을 목적 함수로 하는 다목적 최적화 알고리즘이 널리 사용되고 있다. 그러나 일부 사례에서 나타나듯이, 회전교차로

내 교차구간에서의 혼잡은 지체를 더욱 악화시키지만 이에 대한 연구는 미미한 실정이다. 본 연구는 창원시청 회전교차로를 대상으로 교차구간에서의 밀도를 하나의 목적 함수로 채택하고, 지체시간 및 용량을 또 다른 함수로 선정하였다. 신호주기 및 신호시간을 최적화를 위해 ABFO 알고리즘이 제안되었으며, MATLAB을 통해 계산된 신호주기 및 녹색시간은 VISSIM을 통해 분석되었다. 그 결과 102초 (현시1 – 65초 및 현시2 – 37초)의 신호주기가 산출되었다. 이는 일반 회전교차로와 비교 시 46.1%의 밀도 및 32.8%의 지체시간 감소효과가 있으며 14.8%의 회전교차로 용량 증대효과가 나타나는 것으로 분석 되었다.

키워드

신호 회전교차로, 녹색시간, 최적화, VISSIM, hybrid GSA-ABFO algorithm.