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Intelligent Urban Road Traffic Management at a Crossroads based on Genetic Algorithm

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ABSTRACT

The present paper is mainly concerned with the issue of developing an integrated nonlinear model that aims to minimize the waiting time of the crossroads users including cars, HGVs and trams. It takes into consideration the constraints related to the pedestrian safety and the crossroads structure.
Given the complexity of the crossroads management system due to infrastructure and security constraints, on one hand, and the non-linearity of some equations and the independent variables to be considered, on the other hand, the genetic algorithm (GA) appears to be most suitable to solve such problem as it supplies satisfactory results in real time compared to the semi-adaptive system and no-adaptive system. The experiment was run on a simple four-light crossroads, and a six-light roundabout considered as one of the most important and complex crossroads in Casablanca.

General Terms:

Lights color, An adaptive regulation system

Keywords

An adaptive regulation system, crossroads, genetic algorithm, lights color, traffic control.

1. INTRODUCTION

The issue of traffic congestion has become seriously irritating especially with the continuous increase of the number of vehicles being used. The need for an adaptive and optimal management of crossroads is urgently demanded. This critical demand emanates from a number of worrying observations made in the actual management models, observations having to do with long vehicles queues, slow traffic movement and subsequently long trip time. Furthermore, the priority allotted to the tram, police vehicles and ambulances; and the absence of appropriate lanes for buses and large vehicles are some of other factors that worsen the problem of traffic jams as well. With the opportunities that advanced technology offers, it becomes possible to revisit the actual management methods and even substitute them with more adaptive responsive ones. Thanks to the availability of sensors placed on the intersections, it becomes easy to accurately collect data regarding the traffic movement situation on real time. This option leaves room to accurate and quick decision making process. It also requires easy installation and less maintenance. The data provided by these sensors are the core input of the management system.
As aforementioned a simple crossroads has complex characteristics; and therefore, it is difficult to describe it by a precise mathematical model; in [1] and [2] the authors use systems of signal control based on the fuzzy logic. The systems using a mathematical model differ by the nature of the decision variables, the security constraints taken into consideration, the criteria to be minimized and the resolving methods. In [3], the criterion is the queue length, and the variables are the start time of the green state and the green time. In [4], a mesoscopic model is used; the variables are the sequence of vehicles group crossings; In [5], Dujardin shows that acyclic systems are more flexible than cyclic systems. He develops three models with the same objective function, three criteria but different variables.
In the present article a new approach to crossroads management is suggested based on a mathematical model that makes use of genetic algorithms. Section 2 provides a description of the proposed model along with its operational benefits. The genetic algorithm [6] developed to fulfil the requirement of this model is presented in section 3. Section 4 presents the numerical results and compares the findings to the available semi/non-adaptive management systems with respect to the crossroads sample [7] that have been chosen in this study.

2. MATHEMATICAL MODEL

2.1 Mathematical model

The present work is devoted to designing a system allowing a micro-control of crossroads in real-time by choosing an optimal green time that enables maximum flow of vehicles standing by in front of the lights. Given the different types of variables involved in the light switching decision, the optimal modelization of such situation would be developed with mixed decision variables:

—The light state is a boolean variable, it's equal to 1 if it is green and to 0 otherwise. It is represented as follows:

$$x_{p,f} = \begin{cases} 0 & \text{if the light is red .} \\ 1 & \text{else.} \end{cases}$$

It is denoted by H the duration of the time horizon.

—The switching dates. The pth switching date of light f is presented by $d_{p,f}$.

The time interval [0; ...; H] contains n switching dates between the moment $d = 0$ and the date $d = H$.
Macroscopic modelling is adopted in this study for some pertinent reasons. First, it is suitable for the type of input considered in this experiment, which corresponds to the vehicle flow rates instead of individual vehicles crossings. Furthermore, this choice goes in accordance with the type of information provided by the sensors. Within this perspective, the computational running time is shortened; and, thus, the processing in this model is more simplified than in the microscopic model. Hence we consider:

—$DA_{p,f}$: the input traffic stream on the light f at the p^{th} switching date.

—$DS_{p,f}$: the output traffic stream on the light f at the p^{th} switching date.

As for the HGVs such as buses, lorries and trams, they require a microscopic processing as they have a low arrival frequency. It is to be noted that for the same reason the choice of this type of modeling does not increase the calculation times, thus we consider:

—Nf the number of traffic lights.
—$xtr_{p,f}$: Is a boolean variable that equals 1 if we have a tram arrival between $d_{p,f}$ and $d_{p+1,f}$ and it is 0 otherwise.
—tq_i: The ith departure moment of tram.
—tp_{tram}: The necessary time for the tram passage.
—ta_i: The ith arrival moment of tram.
—R_{tram}: The tram waiting time.
—n: Number of arriving tram on H.
—$xG_{p,f}$: is a boolean variable. It equals 1 if there is a HGV arrival in light f between $d_{p,f}$ and $d_{p+1,f}$, and it is 0 otherwise.
—tp: The necessary time for the HGV passage.
—taG_f: The arrival moment of HGV in light f.
—tqG_f: The departure moment of HGV.
—R_{HGV}: The HGV waiting time on the crossroads.

The model can be formulated as follows:

$$\begin{cases} \min\limits_{X} FA(X) \\ s.c \;\; X \in C_X \end{cases}$$

where the objective function FA is defined with the equations: (1–5) and the constraints set:
$C_X = \{X \in \Omega \, / \, X$ verifying the constraints: (7–14)$\}$
$X = (d_{p,f}; x_{p,f}; xtr_{p,f}; xG_{p,f})$
$\Omega = [0; ...; H] \times \{0;1\} \times \{0;1\} \times \{0;1\}$

The main aim of this stage of optimization is to convert the input traffic flows into processable outputs bearing the following criteria:

(1) The tram waiting time (1) is the difference between departure and arrival moment during H.

$$R_{tram} = \sum_{i=1}^{n} (tq_i - ta_i) \qquad (1)$$

(2) The total HGV waiting time (2) is the difference between its departure moment and its arrival moment during all the light shifts.

$$R_{HGV} = \sum_{p=1}^{n} \sum_{f=1}^{Nf} (tqGf - taGf) \qquad (2)$$

(3) The waiting time (3) of all vehicles during the switching of lights is the accumulation of the queue length $l_{p,f}$, when it exists.

$$R = \sum_{f=1}^{Nf} \sum_{p=1}^{n} 1/2 \times (l_{p,f} + l_{p-1,f}) \times \min(\Delta d_{p,f}, \Delta d^0_{p,f}) \qquad (3)$$

$\Delta d^0_{p,f}$ in (3) is the necessary clearance time of the queue $l_{p,f}$ on the light f from $d = d_{p,f}$. This time equals $l_{p,f}/DS_{p,f}$ in the green case and positive infinity in the red case.

$$l_{p,f} = \max(l_{p-1,f} + (DA_{p,f} - (x_{p-1,f} \times DS_{p,f})) \times (d_{p,f} - d_{p-1,f}), 0) \qquad (4)$$

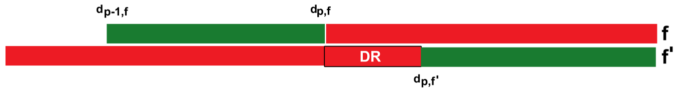

Fig. 1. The red clearance.

$l_{p,f}$ (4) represents the queue length, in number of vehicles on the light f, at $d_{p,f}$.

$$\Delta d_{p,f} = d_{p,f} - d_{p-1,f} \qquad (5)$$

(5) is the period between two successive switches.
Nonlinear model :
In the present model the queue is processed in correlation with the switching dates. The waiting time, on the other hand, is a function of the queue and the switching date as well. This inter-correlation of our decision variables makes this model nonlinear.
In order to minimize all these criteria it is optimal to use the weighting method [8] with preferential parameters to be adapted according to the traffic situation, and the regulation policy. As a case in point, the tram has the absolute priority; the waiting time accordingly is assumed to equal zero. Exceptionally, when we have a constraint like the crossing of an ambulance, the system must bypass that priority.
Let α, β and γ be the weighting factors.

$$Min : FA = \min(\alpha R + \beta R_{tram} + \gamma R_{HGV}) \qquad (6)$$

It is concomitantly prominent to take into account the constraints associated with the crossroads structure:

(1) Antagonist's notion:
When there are two trajectories of different directions; that is to say, they cross each other, they cannot be given the right of way at the same time. That is why lights, in this case, cannot have the green state simultaneously. We call these two lights antagonist lights.
Therefore, let f and f' two antagonist lights, their binary state cannot equal 1 simultaneously:

$$x_{p,f} + x_{p,f'} \leq 1 \qquad (7)$$

(2) The red clearance:
It refers to the minimum period to free the intersection; it denotes specifically the time between the shift of light f to red, and the shift of its antagonist to green (see Figure 1).

$$\min(d_{p,f} - d_{p,f'}) = (x_{p-1,f} - x_{p,f}) \times DR \qquad (8)$$

(3) Minimum and maximum time:
Maximum green time (DVmax) stands for the longest allowable duration of the green interval. It represents the maximum amount of time that a green signal indication can be displayed in the presence of conflicting demand. It is used to limit the delay of any other movement at the intersection. The maximum green value in this sense should exceed the green duration needed to serve the average queue.

Minimum green (DVmin) is the shortest allowable duration of the green interval.

$$DVmin \times x_{p,f} \leq \Delta d_{p+1,f} \leq DVmax \times x_{p,f} + M(1 - x_{p,f}) \qquad (9)$$

Maximum red (DRmax) is the longest allowable duration of the red interval.

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Table 1. The possibilities number in function of the lights number.

Nf	the possibilities number
4	$45^4 = 4100625$
6	$45^6 = 16815125390625$

Minimum red (DRmin) is the shortest allowable duration of the red interval.

$$DRmin\times(1-x_{p,f}) \leq \Delta d_{p+1,f} \leq DRmax\times(1-x_{p,f})+M \quad (10)$$

Where M is a positive real number: $M \leq max(DRmax; DVmax)$ and $n > H/\min(DVmin; DRmin)$

(4) Tram's priority:
The tram must have the right of way, all lights having a perpendicular intersection with its lane must pass to red (11) at the arrival moment ta_i (12).

$$x_{p+1,f} \leq (1 - xtr_{p,f}) \quad (11)$$

$$d_{p+1,f} = ta_i \quad (12)$$

The lights must reset to their previous state after a duration that corresponds to the tram crossing (13).

$$d_{p+2,f} = ta_i + tp_{tram} \quad (13)$$

(5) HGV's priority:
Priority is given to buses and large vehicles once they leave their standby position, Accordingly, the red time of their antagonistic lights is extended in order to allot the necessary time for the HGV flow.

$$d_{p+1,f'} \geq (tqG_f + (tp)) \times xG_{p,f} \quad (14)$$

Equation (14) means that a large vehicle (HGV) has priority if it leaves its light.

2.2 The complexity

To make decision of switching dates in a crossroads composed by $Nf = 4$ lights and an interval $[\min(DVmin, DRmin); \min(DVmax, DRmax)]$ containing NB seconds, each moment must be tested with each instant of every interval of the other lights (see figure 2) in order to find the optimal arrangement, therefore, there will be NB^{Nf} possibilities.
We present in table 2.2 the number of possibilities according to the lights.
In a network of NC crossroads there will be NB^{Nf*NC} possibilities.

3. THE APPLIED ALGORITHMS

3.1 The applied Branch and Bound algorithm (B&B)

We choose the algorithm (B&B) (algorithm 1) for our problem wish is a combinatorial optimization problem.

3.2 The applied genetic algorithm (GA)

We adopt in this solution the use of a metaheuristic because it is more suitable for nonlinear models.
As for the use of the genetic algorithm (see Figure 3) the following list provides arguments that support its implementation:

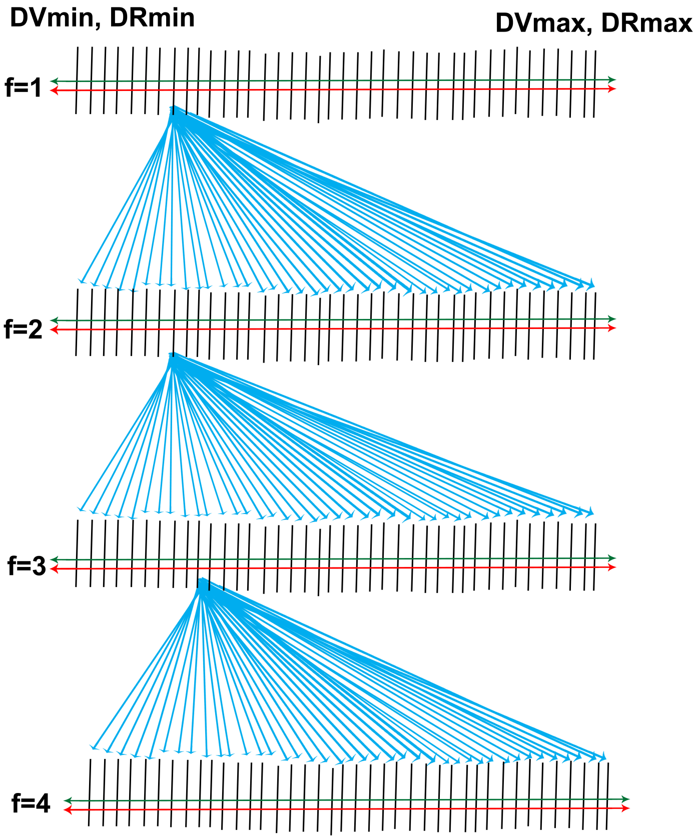

Fig. 2. The possibilities.

Algorithm 1 The applied Branch and Bound algorithm (B&B)

i=1
$NB = \min(DVmax, DRmax) - \min(DVmin, DRmin)$
$d_{p,1} = d_{p-1,1} + \min(DVmax, DRmax)$
for $i \leq NB$ **do**
  Calculation $d_{p,2}, d_{p,3}, d_{p,4}$ ($d_{p,1}$, the constraints)
  solution[i]={$d_{p,1}, d_{p,2}, d_{p,3}, d_{p,4}$}
  Calculation of the delay caused on the crossroads by the solution[i].
end for
Selection of the best solution minimizing the objective function.

—Genetic algorithms are the solution to the optimization problems. They operate quickly, reliably and accurately in real-time [9].

—Genetic algorithms fit well in the present study: the output variables are the switching dates of the lights. They are integers that we encoded into binaries. It is the most common form of encoding in which the data value is converted into binary strings. Binary encoding gives many possible chromosomes (the switching dates) with a small number of alleles.

—Genetic algorithms are commonly used in situations similar to the one in the present study.

Initialization: Create a set of feasible solutions satisfying the constraints.

↓

Evaluation 1: Calculation the objective function of parents.

↓

Selection 1: Selection the best $d_{p,f}$ according to the selection of elitism.

↓

Coding the parents in binary on 8 bits.

↓

Crossover: Crossing with a crossover probability p_c

↓

Mutation: Mutation with mutation probability ($p_m \in [0,01;0,1]$.

↓

Decoding the sons in decimal and replacement unfeasible sons by their parents.

↓

Evaluation 2: Calculation the objective function of sons.

↓

Selection 2: Selection the best $d_{p,f}$ between the parents and the sons according for the replacement.

↓

Repeat the algorithm a number of iterations.

↓

Take $d_{p,f}$ the date of switching which minimizes the objective function.

↓

Go to the next switch.

↓

The solution is a switchings set for each light in the time horizon H.

Fig. 3. The Scheme of the applied genetic algorithm.

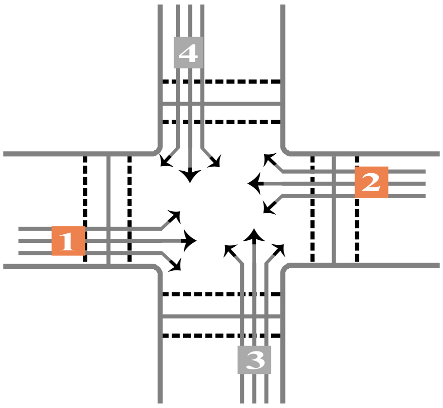

Fig. 4. Crossroads structure of four lights.

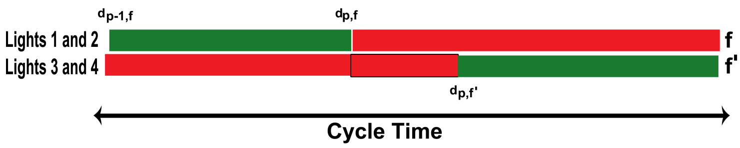

Fig. 5. The simple crossroads cycle.

4. NUMERICAL SIMULATION

4.1 A crossroads of four lights

The test of the genetic algorithm is performed in a simple crossroads containing 4 lights (see Figure 4) where each of the lights 1 and 2 is antagonist of lights 3 and 4 and vice versa. The cycle of this crossroads type is represented in Figure 5:

(1) Both lights 1 and 2 shift to green simultaneously.

(2) After a duration $\Delta d_{p,f}$ lights 3 and 4 turn green at the same time.

In this type of crossroads like the intersection between "Zerktouni street" and "Brahim Roudani street" in Casablanca there is no tram lane, and a switching of one light entails the switching of the other lights.
A duration of 180 seconds is assigned to the time horizon H, and the switching number NC equals 3.
The constants and the values provided by the sensors are represented in table 4.1.
A no-adaptive system S:
It is known that the duration $\Delta d_{p,f}$ is fixed for a no-adaptive system as the traditional traffic lights (see Figure 5). For the most adaptive systems, however, it is non-fixed even though the cycle time is fixed. In our system neither the phase timing nor the cycle is fixed; it is an acyclic system seeking the optimal duration minimizing the criteria by checking the model constraints. The crossroads (C) (Rond Point Hassan II) (see Figure 6 and 7) contains six lights.
A semi-adaptive system (S'):
The green intervals vary depending on the parts of the day. The

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Table 2. The constants and the values provided by the sensors of the crossroads with four lights

Variable	Value
$DRmin, DVmin$	15
$DRmax, DVmax$	60
DR	8
tp	20
taG_f	The matrix N
tq_i	0 50 80
$l_{p-1,f}$	0 0 0 0
$x_{p-1,f}$	1 1 0 0
$d_{p-1,f}$	10 10 18 18

where N is the matrix

$$N = \begin{pmatrix} 20 & 0 & 123 \\ 0 & 0 & 0 \\ 0 & 0 & 130 \\ 0 & 80 & 0 \end{pmatrix}$$

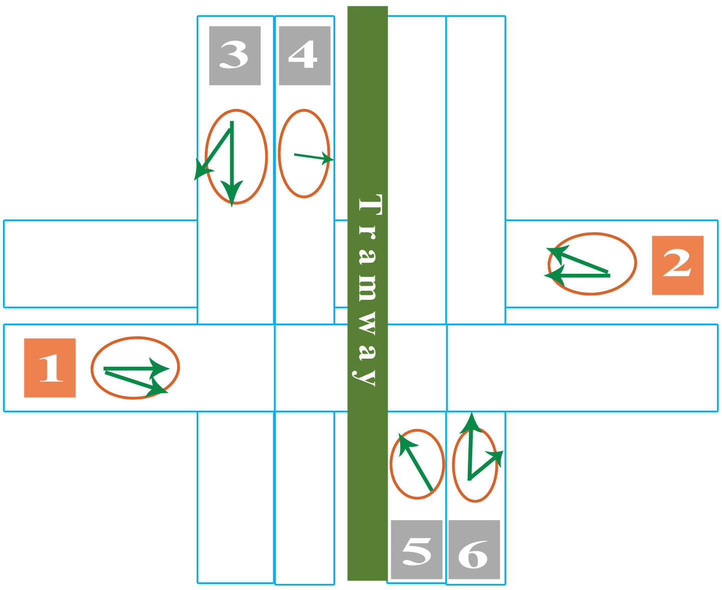

Fig. 6. The crossroads (C) drawn with the path of the Tram.

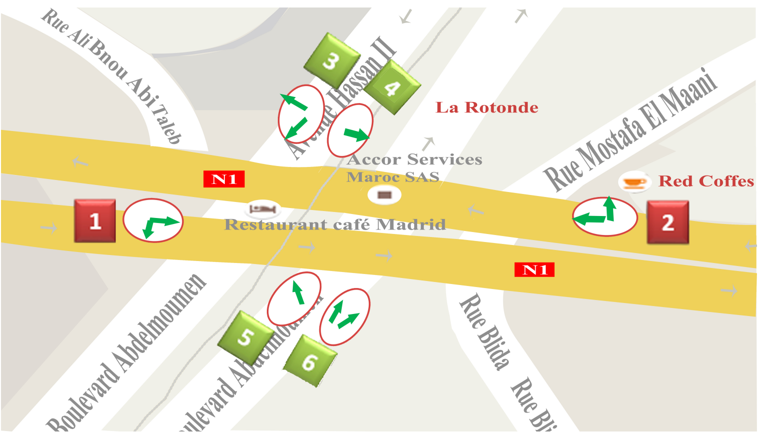

Fig. 7. Structure of the crossroads (C) from Google Maps

crossroads cycle is described as follows (see Figure 8):

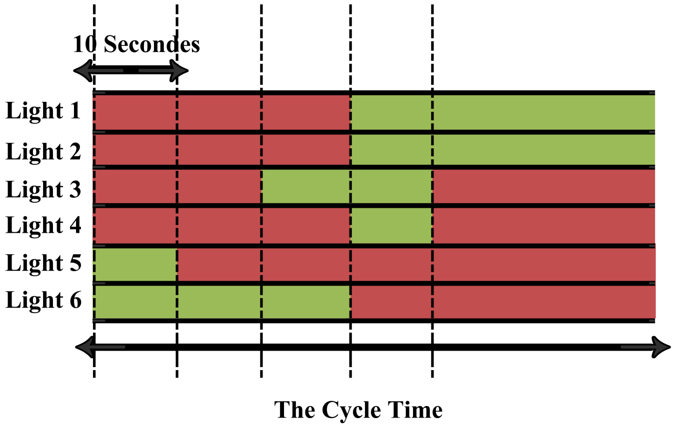

Fig. 8. The cycle of crossroads (C)

Table 3. The constants and the values supplied by the sensors of 'Rond Point Hassan II'

Variable	Value
$DVmin; DVmax$	25 45
$DVmin; DVmax$	10 20
DR	8
$l_{p-1,f}$	0 0 0 0 0 0
DA_f Pick hours	0.5 0.5 0.2 0.2 0.2 0.2
DA_f Other hours	0.3 0.3 0.1 0.1 0.1 0.1
DS_f	0.4 0.4 0.3 0.3 0.3 0.3
$x_{p-1,f}$	0 0 0 0 1 1
d_{p-1}, f	8
ta_{tram}	20 50 80

(1) A switching of lights 5 and 6 to green triggers all the other lights into red.

(2) After 10 seconds; light 5 turns red with all other lights, and the light 6 stays green.

(3) After 10 seconds, light 3 shift to green, the light 6 stays green and all the other lights are red.

(4) After 10 seconds, light 4 goes green; meanwhile, light 3 stays green and light 6 turns red along with all the other lights since the vehicles in lights 1, 2, 5 and 6 have a perpendicular intersection with those of light 4.

(5) After 10 seconds, lights 1 and 2 change to green which spans 50 seconds at peak hours and is reduces to 35 seconds elsewhere.

The sets of compatible lights can be classified as follows: (1, 2); (3, 6, 4); (3, 6, 5); (3, 6, tram). During the passage of the tram only lights 3 and 6 are green because they do not have an intersection with the tramway.
In this kind of crossroads with a Tram lane; the passage of large vehicles is forbidden. In this case the variables inherent to HGVs are not included.
The difference between our system and the system (S'):
In our system we respect only the order of the phases in the cycle while other parameters are subject to variation. This is so because we seek to optimize the duration for all the lights in a way that accords with the criteria and the constraints of the model.

4.2 The input data of 'Rond Point Hassan II'

The constants and the values provided by the sensors for this case are represented in Table 4.2.

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Table 4. Comparison of FA supplied by the AGA, S and the $B\&B$ i
seconds of the simple crossroads

	AGA	CPU time	S	CPU time	$B\&B$	CPU ti
Low						
μ	2027.6	0.006	2343	0.002	1085	0.078
σ	575.41	0.002	0	0.006	0	0.014
Middle						
μ	3656.47	0.015	4264	0.0008	1742	0.099
σ	1031.587	0.013	0	0.0005	0	0.073
High						
μ	5503.30	0.016	6184	0.002	2401	0.077
σ	1676.684	0.036	0	0.003	0	0.011

4.3 Comparison

The present system is implemented by the solver MATLAB (version 2010), on Intel Core duo i7 CPU 2.40 GHz, 4 GB RAM and the operating system windows 10 (64 bit) with an average running time of 11 seconds. The model being presented, on the other hand is solved by the genetic algorithm (GA) and the B&B applied to the crossroads (C), by the GA and the B&B to a simple crossroads of four lights.
The crossover probabilityp_c chosen equals 0.95 and a mutation probability p_m between 0.01 and 0.1 for all tests because they give the best results.
Because GA is a probabilistic stochastic search algorithm, the objective function (FA) takes different values from different runs on the same circumstances, therefore, the average value of the results compared to the results provided by the no-adaptive system S and the B&B method is considered.
The table 4.3 shows a comparison of the average values of (FA) in the simple crossroads generated by our system (AGA), a no-adaptive system S with phases of 45 seconds and the B&B method in terms of the traffic stream variation.

—A low traffic stream: the input traffic stream: DA_f = [0.1 0.1 0.1 0.1] and the output traffic stream: DS_f= [0.1 0.1 0.1 0.1].

—A middle traffic stream: the input traffic stream: DA_f = [0.2 0.2 0.2 0.2] and the output traffic stream DS_f= [0.2 0.2 0.2 0.2].

—A high traffic stream: the input traffic stream: DA_f =[0.3 0.3 0.3 0.3] and the output traffic stream DS_f= [0.3 0.3 0.3 0.3].

To visualize the differences, Figure 9 presents the waiting time comparison provided by the systems in minutes, in terms of the traffic stream variation for each vehicle crossing the network.
Figure 10 shows the average CPU time for all systems in seconds.

According to Table 4.3, figure 10 and figure 9 AGA system performs well both in terms of the waiting time and CPU time. It minimizes the waiting time as compared to S system, and exhibits the best CPU time with regard to B&B for all traffic stream (high, middle or low).
The Table 4.3 provides the values of the objective functions in the crossroads C issuing from from AGA system and a semi-adaptive system (S').
All results in both cases showed that system being discussed gives the best results.

5. CONCLUSION

In the present study we addressed the issue of urban traffic management at two isolated crossroads. The aim of optimizing the decision making regarding light switching was successfully achieved by adopting a nonlinear approach.

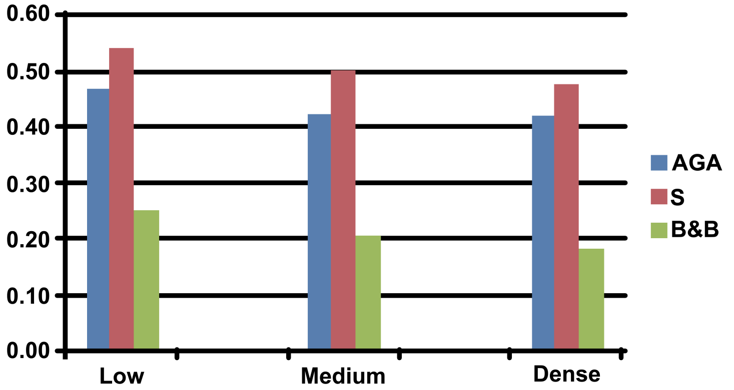

Fig. 9. The average waiting times provided in minutes with respect to the variation traffic stream for each vehicle.

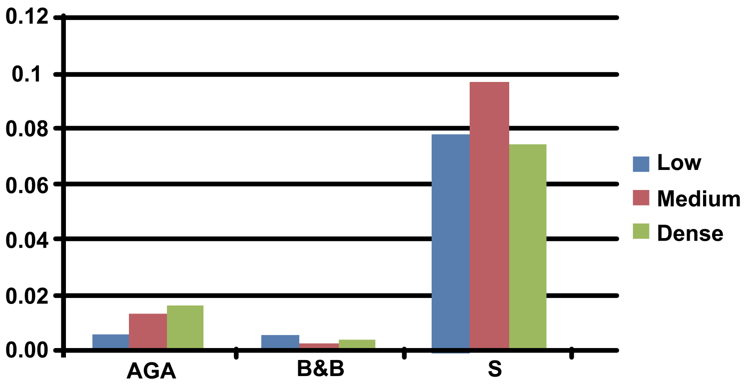

Fig. 10. The average CPU time for the simple crossroads.

Table 5. Comparison of FA supplied by the AGA and (S') in seconds at 'Rond Point Hassan II'

	(S')	CPU time	AGA	CPU time
Pick hours	7782	0.002172	4811	0.021605
	7782	0.001487	5309	0.012601
	7782	0.002315	5110	0.006285
	7782	0.002010	5199	0.009986
	7782	0.001549	4360	0.009645
	7782	0.001713	6124	0.003960
	7782	0.001677	4690	0.003452
	7782	0.002286	6198	0.003898
Other hours	2421	0.032418	2484	0.033343
	2421	0.004322	1992	0.013975
	2421	0.019431	2061	0.005196
	2421	0.004146	2615	0.005738
	2421	0.002803	2411	0.009049
	2421	0.001908	2349	0.004066
	2421	0.001721	2010	0.014468
	2421	0.002860	3094	0.007799
	2421	0.002361	2154	0.004222

When contrasting this method with the no-adaptive method, the results support the suggested model and prove the effectiveness of genetic algorithms in the optimization of the traffic waiting time at a complex crossroads. In the future work we will apply the model to an interrelated network of crossroads using B&B and GA as methods of resolution.

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