

Fixed Time Traffic Signal Optimization in Urban Networks using a Simulation-Based Multiobjective Algorithm

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Abstract: The increasing number of vehicles and pedestrians in the cities increases difficulties for traffic management. Nowadays applications of computational techniques can help traffic engineers, giving more efficiency, security and agility to decision making tasks. In this context, a good traffic signal optimization may improve vehicles flow, decreasing traffic jams and delays. This paper applies a multiobjective technique to traffic signal optimization using Nondominated Sorting Genetic Algorithm (NSGA-2), aggregates the proposed algorithm with a microregion traffic simulator coupled into Geographic Information System (GIS). Experiments performed in a region inside Belo Horizonte (Minas Gerais state, Brazil) validate the applied technique, comparing obtained results with data collected from actual operation at the same region.

Keywords: Traffic Signal Optimization, NSGA-2, Multiobjective Algorithm, Simulation

1 INTRODUCTION

Nowadays the large cities deal with serious problems in the traffic management because of the increasing number of vehicles and pedestrians. According to the Traffic Engineering Company of Sao Paulo (CET-SP)'s report CET-SP (2010), the traffic flow increased by 34.2 percent between 1997 and 2009. In the same period, the population grew only 8 percent. In addition, the rotation of vehicles (strategy to improve the traffic) has totally lost its effects, 13 years after to start. The average speed decreased from 17.49kmh in 1997 to 11.7kmh in 2009, i.e., 33 percent in total.

The large number of vehicles is the main aggravating factor for this problem. According to Urban Mobility report from the Transport and Transit Company (BHTRANS) of Belo Horizonte, Brazil, the car fleet increased from 491,332 to 937,819 units, i.e., 91 percent of the total. At the

same time, motorcycles fleet increased further, totalling 226 percent, from 44,634 to 163,489 units. Considering other types of vehicles, the total fleet has increased 10 percent by year, which indicates the need for constant improvements in traffic management.

The benefits of increasing average speed in urban networks are significant, and a lot of research has been done in this area. According to OECD (2006), the average speed optimization represents best production for business activities, lower travel times of the public transportation, and it is critically important for several essential services such as ambulances, fire department and police. In this context, traffic signal optimization is one of the most important techniques to reduce traffic congestion, fuel consumption, number of stops, among other problems.

Several studies involving traffic signal optimization can be found in the literature. Webster (1958) used deterministic methods to configure signal cycles for isolated intersections. Thereafter efforts focused to the traffic signal optimization in networks (Allsop and Charlesworth, 1977) (Charlesworth, 1977). Moreover, Genetic Algorithms (GA) were applied to optimize isolated intersections, arterial roads and traffic networks (Foy et al., 1992) (Hadi and Wallace, 1993) (Oda et al., 1996) (Park, 1998) (Rouphail et al., 2000) (Masterton and Topiwala, 2008) (Turky et al., 2009) (Sánchez et al., 2010). When emerged the multiobjective evolutionary algorithms, in the beginning of this century, they were applied to perform traffic signal optimization in isolated intersections (Sun et al., 2003) (Hu et al., 2010).

This paper proposes a fixed time traffic signal optimization approach for urban networks using a multiobjective algorithm and microscopic simulation. In this context, we propose and implement a model with two objective functions: to maximize the cars average speed, and to minimize the speed variance in urban networks. For this, the Nondominated Sorting Genetic Algorithm 2 (NSGA-2) (Deb et al., 2002) is applied to simultaneously optimize these functions. In addition, the microscopic simulator GISSIM (Neto et al., 2010) evaluates the candidate traffic signal plans. Experiments performed in a simulated area of Belo Horizonte (Minas Gerais, Brazil) show that this approach is efficient, improving the current traffic conditions.

The paper is structured as follows. Section 2 presents concepts of traffic signal optimization and Section 3 explains the proposed method. Practical experiments and comparison of results with technical literature are presented in Section 4. Finally, Section 5 provides conclusions and perspectives to future works.

2 TRAFFIC SIGNAL OPTIMIZATION

Inside a transportation context, a movement identifies the source and destination of vehicles in a traffic network. Two movements are conflicting when they cross at an intersection. Figure 1 shows the scheme of an intersection with two one-way streets and their allowed movements, along with its corresponding Stages Diagram, which illustrates allocation of movements for each stage (CONTRAN, 2012).

Traffic signal is a control device that coordinates the drivers and pedestrians flow in intersections

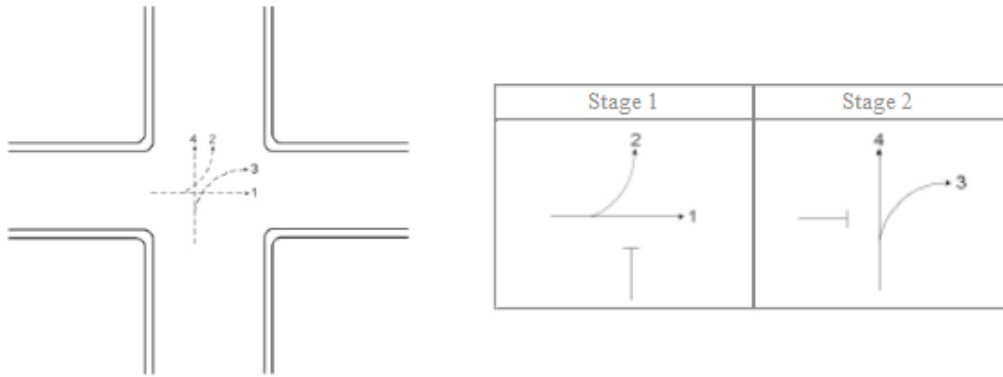


Figure 1: Intersection with four allowed movements, and its Stages Diagram. Adapted from DENATRAN (1984)

with two or more incoming roads. In this sense, some concepts are important to be understood when we are studying traffic engineering. According to CONTRAN (2012), a *cycle* is the total time (in seconds) for the complete signaling sequence in an intersection. A *phase* is a sequence of colors applied to the traffic flow, and usually each phase of a cycle corresponds to a physical traffic signal in the street. *Stages* are the time periods of the phases corresponding to the signaling (red or green colors). An *intergreen* period is the time spent between the end of a stage and beginning of a new one. A *Time Diagram* associates changing moments, colors sequences and phases length. Figure 2 shows a Time Diagram for the intersection shown in Figure 1.

Phase 1	GREEN	Y	RED		G1 (mov 1 and 2)
Phase 2	RED		GREEN	Y	G2 (mov 3 and 4)
Stages	1	l_1	2	l_2	
Dimension (sec)	30	3	24	3	
Dimension (%)	50	5	40	5	
	← Cycle →				

Figure 2: Time Diagram with two phases and two stages. Adapted from DENATRAN (1984)

Traffic signal optimization means the definition of operation parameters for a given traffic network over time. These operational parameters form together a *Traffic Signal Plan*, which in turn should contain the following parameters for each intersection: number, sequence and length of phases and stages, cycle time, and offset times. These parameters must be carefully defined because they might cause traffic jams, delays, drivers disrespect, increase of pollution, reduction of security, among other problems. Monteiro (2008) says that traffic signal optimization should be a security measure to reduce car accidents.

2.1 Some Relevant Work

Sun et al. (2003) reported an interesting research about traffic signal optimization using the Non-dominated Sorting Genetic Algorithm 2 (NSGA-2). They proposed a model with two objective functions: average delay and number of stops. The Webster method was used to calculate these functions to qualify solutions generated by NSGA-2. In order to investigate the application of that model, the authors created a scenario with one isolated intersection of two phases. The results showed that multiobjective GA had potential to be used in the problem. In addition, they concluded that NSGA-2 algorithm found multiple near-optimal solutions according to Webster Method. However, the authors asserted that the application of this technique for traffic signal networks should be further studied.

Hu et al. (2010) presented a multiobjective model of fixed time traffic signal control for unsaturated isolated intersections. In that model, the optimization variables used were cycle length and green times. Moreover, the model was defined with three objective functions: average of vehicles delay, average number of vehicle stops and maximum relative size of traffic jams. These equations belong to the Webster Method. They used NSGA-2 to optimize the functions set in an intersection at Yangpu, Shanghai. The results were compared to the Webster Method, and their technique decreased the average delay in 47.9 percent, decreased maximum relative size of traffic jams in 48.3 percent, meanwhile it lightly increased the number of stops in 3.3 percent, verifying the efficiency of the proposed approach.

Costa et al. (2011) presented a multiobjective model of traffic signal optimization in an urban network. In that approach, the model adopted the green times as the decision variables to optimize two functions: maximize number of vehicles leaving the network and minimize travel time of vehicles. The NSGA-2 algorithm optimized the functions with a microscopic simulator GIS-SIM coupled to geographic information system OpenJUMP to evaluate the solutions. Experiments were performed in a simulated scenario of Porto Alegre with 13 intersections. The results showed that several efficient solutions were generated in a single run, besides having improved the mono-objective GA result proposed by Oliveira and Almeida (2010).

3 Proposed Method

The approach here proposed is a fixed time traffic signal optimization for a region composed by various intersections. Our technique combines modeling of traffic signal plans in urban networks, an NSGA-2 algorithm (Deb et al., 2002), and a microscopic simulator GISSIM (Neto et al., 2010), as seen in Figure 3.

3.1 NSGA-2 Algorithm

The evolutionary multiobjective algorithm NSGA-2 was proposed by Deb et al. (2002) to improve existing proposals. Figure 4 shows the general scheme of the algorithm.

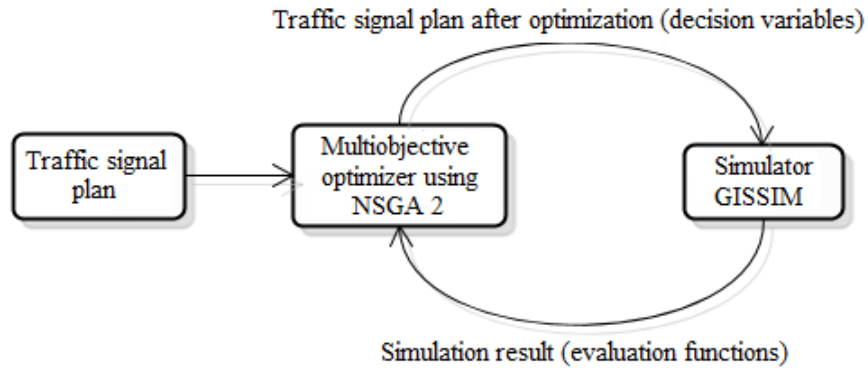


Figure 3: Technique proposed to solve the traffic signal optimization problem

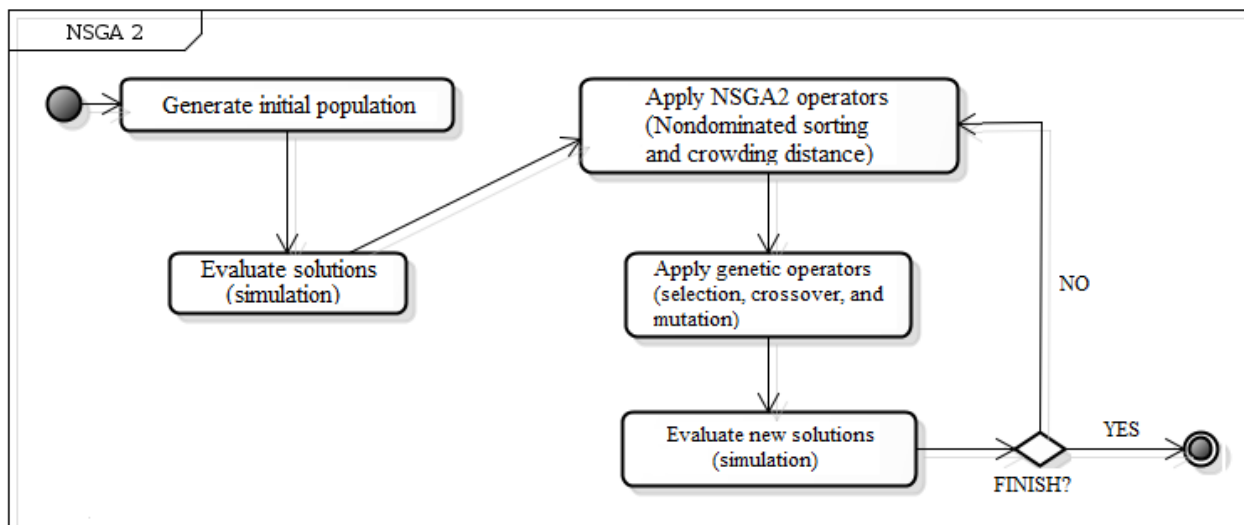


Figure 4: NSGA-2 flow. Adapted from Deb et al. (2002)

The algorithm generates a random solution set and evaluates these solutions using microscopic simulation. Thereafter, the algorithm starts a loop with the following operations: to classify the solutions according to their fronts and crowding distance, to select the best solutions (fathers) to generate the next generation, to apply crossover and mutation operators generating new solutions (children) and, at last, to evaluate children using microscopic simulation. This loop is repeated until the stop criterion is satisfied. In the next sub-sections, some characteristics of the algorithm are presented.

3.1.1 Solution Representation

Each solution has been encoded using binary scheme, and a vector has been used to represent green times of the traffic lights. In Figure 5, sequential numbers show bit strings for each variable (10 bits for each) and the two variables are denoted by white and gray backgrounds respectively.

Vectorial organization symbolizes genetic features (genotype), and the decoded values repre-

Variable 01										Variable 02									
1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
0	1	0	0	0	1	1	0	0	1	1	1	0	0	0	1	1	0	1	1

Figure 5: Solution representation for an hypothetical instance with two variables.

sent real features (phenotype). These features have been decoded using a normalization method presented by Eq. 1,

$$v_{norm} = (v_{bin} * (d_{max} - d_{min}) / (2^p - 1)) + d_{min}, \quad (1)$$

where: v_{norm} represents normalized value, v_{bin} represents decoded binary value, d_{min} represents minimum domain value, d_{max} represents maximum domain value, and p represents precision. For instance, in Figure 5, the normalized values are 18 seconds for the first variable and 34 seconds for the second variable, considering minimum green time as 15 seconds and maximum green time as 40 seconds, for a precision of 10 bits.

3.1.2 Evaluation of Solutions

Initially, a population with individuals representing current traffic signal plans are generated. For this, we are using BHTRANS configuration (cycles, phases, and stages times). The evaluation of solutions uses microscopic simulator GISSIM. For each individual, the decision variables are assigned to the simulated area to run a simulation. After all, the results are collected to calculate objective functions for each solution. Our model proposes to optimize the following objective functions:

- To maximize FX1: average speed of the vehicles;
- To minimize FX2: speed variance of the vehicles.

This combination of functions is different from classical approaches, which used measures of number of stops, average delay of vehicles, traffic jams length, etc. Maximizing the first function means to increase cars average speed and to improve traffic flow. Meanwhile, minimizing the second function means to decrease the difference between the average speed of vehicles and to improve traffic equilibrium in all streets of the given urban network.

3.1.3 Genetic Operators

The following genetic operators have been adopted for evolution of the population: binary tournament selection using crowded comparison operator, uniform crossover with rate verified per pair, and traditional swap mutation with rate verified per bit. More information about these operators and techniques can be found in Deb et al. (2002).

3.2 The GISSIM Simulator

The importance of simulation to help in traffic management is very significant, because it incorporates new features for controlling and planning of traffic in cities (Oliveira and Almeida, 2010). The traffic simulators, especially the microscopic ones, are characterized by requiring a large amount of input data, e.g., the road network shape and flow information for the region to be studied. Assuming that it is increasingly common the use of GIS for municipalities as a tool for urban planning, it is plausible to use such tools as a data source for the purpose of simulation, making it possible to reuse existing spatial information of the road network, such as routes and location of traffic lights, among others, already available for a large number of others cities around the world.

The GISSIM simulator (Neto et al., 2010) performs microscopic simulation of urban traffic. It is integrated to OpenJUMP geographic information system (GIS) platform, allowing to retrieve the geo-referenced informations from digital maps. In addition, GISSIM creates a simulation area using GIS features such as junctions, traffic volume data, etc.

4 Experiments and Results

In this section, we present practical experiments and results in a microregion of Belo Horizonte (Minas Gerais state, Brazil). These experiments are detailed in the next subsections.

4.1 Scenario

The practical experiments were performed for the Raul Soares Square, central point of Belo Horizonte hypercenter which connects the flow from the Amazonas Avenue to the Sete de Setembro Square, the flow from/to the Castelo Branco Elevated Avenue, the flow from the Bias Fortes Avenue to Lourdes and Savassi quarters, and the flow from the Augusto de Lima Avenue to the Afonso Pena Avenue. Figure 6 shows the region represented by Google Maps and by OpenJUMP, respectively.

BHTRANS traffic volume data and traffic signal plans (cycles, phases, stages, offset times) were configured in the region to reproduce a realistic scenario. Figure 7 presents the region digitized inside GISSIM simulator, in which 36 intersections are emphasized with white circles, and 17 input junctions with white squares.

The existing traffic signal groups were initially configured according to BHTRANS traffic plans and the optimization algorithms were executed for two different time schedules to obtain the best performance for the two function evaluations for each day interval.

4.2 Adjusting Parameters Set

Table 1 shows NSGA-2 and GISSIM tuning parameters for each algorithm. They were empirically obtained during the experiments to assure stabilization of optimization solutions while trying to minimize execution time.

The simulation steps are used to evaluate individuals, because it is the GISSIM simulation time. The value of 7200 seconds is the considered stabilization time for the traffic network, for the applied

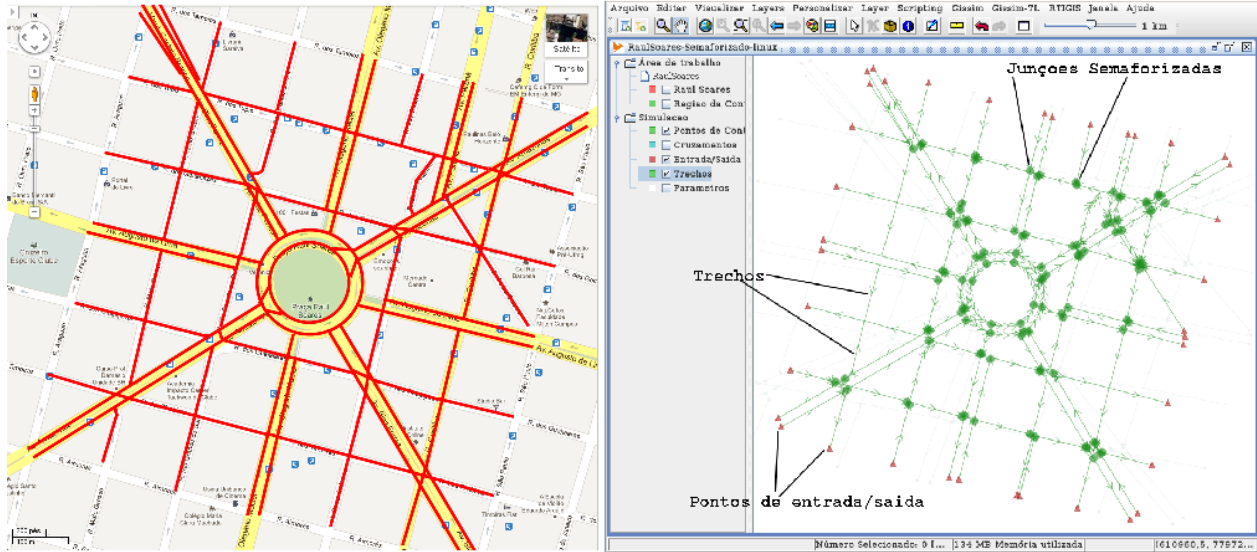


Figure 6: Raul Soares Square represented by Google Maps and by OpenJUMP

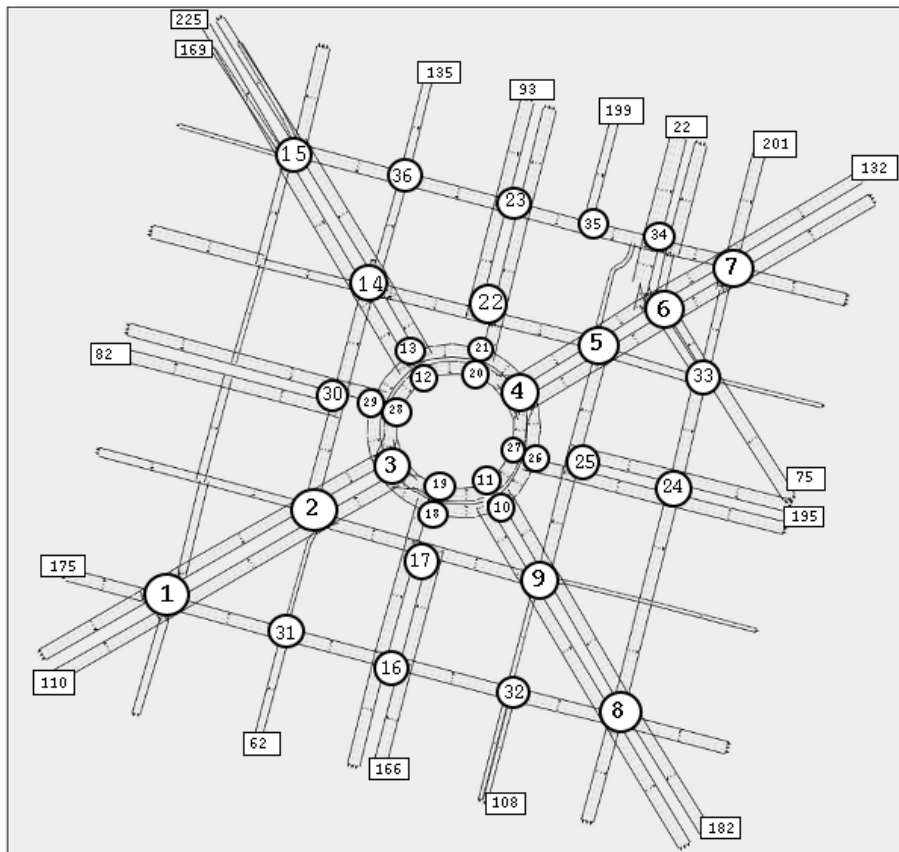


Figure 7: Raul Soares Square represented inside the simulator GISSIM

car flow conditions. This parameter corresponds to 2 simulated hours in the transit. The minimum and maximum stage times correspond to decision variables range, in seconds.

Table 1: NSGA-2 and GISSIM parameters

Parameter	Value
Population size	50 individuals
Number of generations	100
Crossover rate	85%
Mutation rate	3%
Stop criterion	number of generations
Simulation steps	7200 (2 hours)
Min stage time	25 seconds
Max stage time	cycle time - 25 seconds
Yellow time	3 seconds

4.3 Results

In this subsection, the results are presented for the following time periods: from 7:00 to 8:00h in the morning, and from 17:00 to 18:00h. These periods were considered because they represent two of the worst case flow conditions for the urban traffic at Belo Horizonte, and so they would constitute good challenges for the proposed techniques.

4.3.1 Time period from 7:00 to 8:00h in the Morning

First, the traffic volume data were configured inside GISSIM simulator for the time period from 7:00 to 8:00h to run the proposed optimization algorithms in the region. Figure 8 shows typical results for the following traffic signal timing techniques: BHTRANS, GA-FX1, GA-FX2, NSGA-2. Table 2 details the obtained results.

Table 2: Numerical results for the region of Raul Soares Square between 7:00 and 8:00h

Technique	FX1 (Average Speed)	FX2 (Speed variance)
BHTRANS	24.18	179.56
GA-FX1	29.31	165.42
GA-FX2	24.65	143.91

According to the function values, it is easy to see that GA-FX1 results improves the current BHTRANS traffic signal plan (also marked in Figure 8 by a circle). With respect to function FX1, the BHTRANS plan obtained 24.18 km/h on average, while GA-FX1 algorithm obtained 29.31 km/h. These values indicate that average speed of the vehicles is 5.13 km/h higher, i.e., an increase of 21.22%.

For the function FX2, BHTRANS plan obtained a speed variance of 179.56, while GA-FX2 algorithm improved the function value to 143.91, corresponding to a decrease of 19.85%. If speed variance value is transformed to standard deviation, the BHTRANS plan result corresponds to 13.40 Km/h, and GA-FX2 result corresponds to 11.99 Km/h, i.e., a decrease of 1.41 Km/h

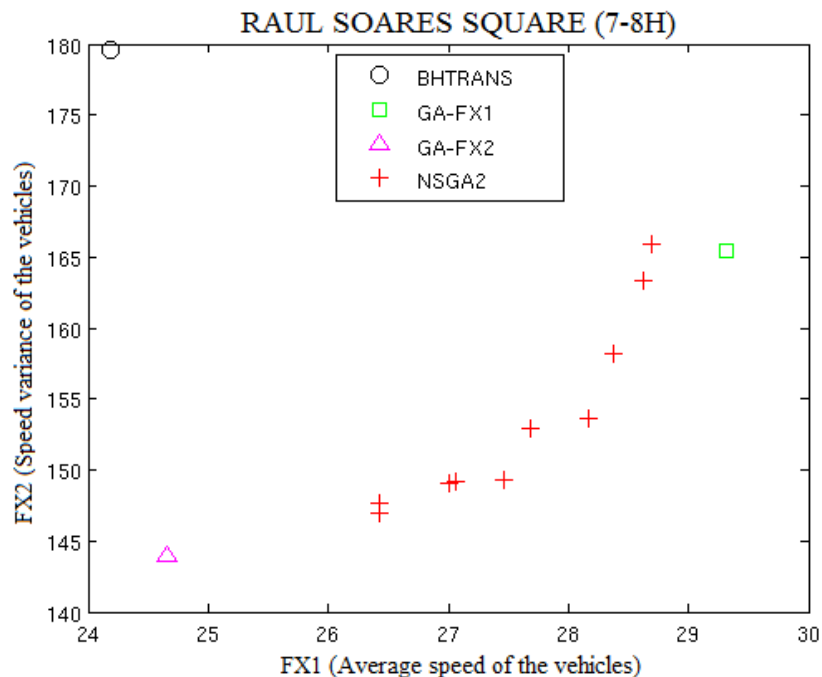


Figure 8: Graphical results for the region of Raul Soares Square between 7:00 and 8:00h

(10.52%).

The solutions obtained by NSGA-2 tend to approach to GA-FX1 and GA-FX2 results. For instance, the extreme solution of FX1 (FX1=29.6 and FX2=156.89) can be compared to the solution obtained by GA-FX1 (FX1=29.58 and FX2=159.72) generated solutions and presents similar quality, while NSGA-2 generated others 9 efficient solutions. This implies that NSGA-2 offers diversity of solutions over the scenario.

This advantage allows for the specialist engineer to choose the desired traffic signal plan, among the solutions obtained by algorithm, for each individual situation presented. For example, if the engineer wants to improve average speed, he chooses a better solution regarding FX1, and if he/she wants to improve speed variance, a better solution regarding FX2 should be chosen.

4.3.2 Time period from 17:00 to 18:00h

After, the traffic volume data were configured inside GISSIM simulator for the time period from 17:00 to 18:00h to run the proposed optimization algorithms in the region. Figure 9 presents the corresponding results. Results are presented for the following traffic signal timing techniques: BHTRANS, GA-FX1, GA-FX2 and NSGA-2. Table 3 shows values for typical individual running of these algorithms.

With respect to function FX1, result of BHTRANS plan corresponds to average speed of 25.95 Km/h, while GA-FX1 algorithm obtained 29.99 Km/h. This value improved the average speed of vehicles in 4.04 km/h, corresponding to an increase of 15.57%. With respect to function

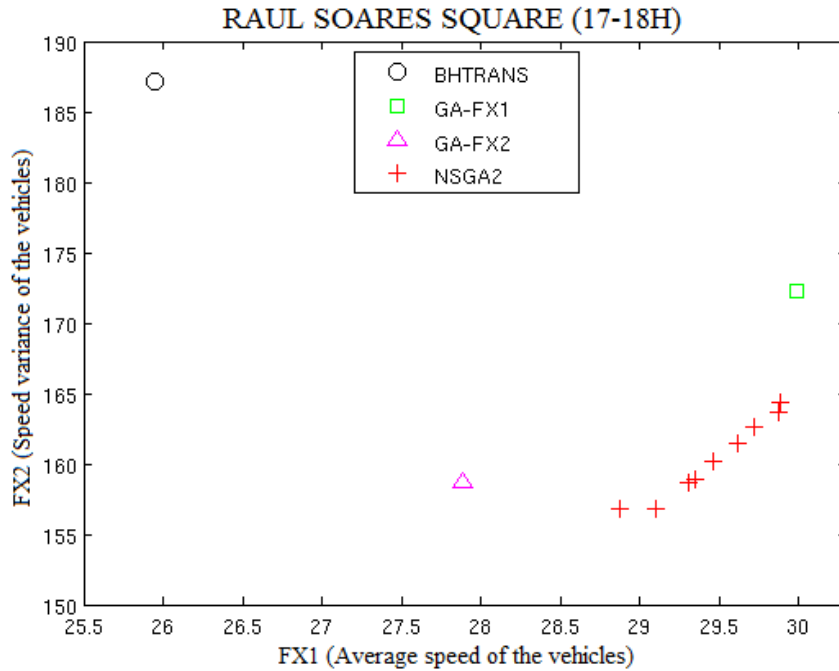


Figure 9: Graphical results for the region of Raul Soares Square between 17:00 and 18:00h

Table 3: Numerical results for the region of Raul Soares Square between 17:00 and 18:00h

Technique	FX1 (Average Speed)	FX2 (Speed Variance)
BHTRANS	25.95	187.14
GA-FX1	29.99	172.30
GA-FX2	27.88	158.66

FX2, the result of BHTRANS plan is 187.14, while GA-FX2 algorithm improved function value to 158.88. This corresponds to a decrease of 15.22\$ in the variance of cars speed in this period.

5 CONCLUSION

This paper presented an implementation of a mathematical modeling for fixed time traffic signal optimization in urban networks, using a multiobjective algorithm and microscopic simulation techniques. In this model, we used two non-usual objective functions: to maximize average speed of the vehicles, and to minimize speed variance of the vehicles. We used multiobjective genetic algorithm NSGA-2 to simultaneously optimize this functions set, and the microscopic simulator GISSIM to evaluate the obtained solutions. Experiments performed in a region of Belo Horizonte (Minas Gerais state, Brazil) showed a significant increase on the average speed of the vehicles, improving the traffic flow. In addition, they showed that the second objective function may generate a more balanced traffic flow in the urban network, improving the so-called network equilibrium. Therefore, we can conclude that this proposal was successfully applied for a given scenario, and that future investigation must be performed in other scenarios to assure the effectiveness and the

generalization properties of the proposed approach.

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