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Metaheuristic Techniques in Optimizing Traffic Control Lights: A Systematic Review

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***Abstract*— Traffic congestion is a serious problem on every roadway and streets in many cities around the world. This systematic review is devoted to analyze research papers that deal with the optimization of traffic signal timing. The main objective of such optimization is maximizing the number of the vehicles leaving the network in a given period of time. This will lead to enhancing the performance of the road system. In this work, we researched the most recent metaheuristic optimized traffic light control techniques. It was shown that integrating optimization techniques in the field of traffic lights control had a great impact on the performance of traffic monitoring. During our research, we found that the most used method was the Genetic Algorithm (GA).**

Keywords*— *traffic light control; systematic review; Genetic Algorithm; Particle Swarm Optimization; Ant Colony Optimization.

I. INTRODUCTION

We are currently experiencing a global energy and environmental crisis [1], [2]. Some statistics reported from two reliable and trusted sources; National Highway Traffic Safety Administration (NHTSA) and US Department of Transportation (US-DOT) showed that the poor traffic light scheduling is the main reason of over half of congestion in US roads in 2011 [3]. They revealed that the poor traffic scheduling caused traffic accidents which results in tens of thousands of deaths associated with traffic and causes property losses [4], [5]. On the other hand, traffic incidences not only cause life losses but also time, fuel, productivity, and money losses [6], [7]. According to (US-DOT) studies, around 3 billion gallons of fuel are wasted each year and 5.5 billion hours are wasted on the roads, which reduce the productivity of the residents in the US dramatically. Furthermore, this increases the air pollution crisis caused by releasing 56 billion pounds of CO_2 [3].

For instance, The United Arab Emirates is attempting to increase the use of public transport. In total, there were 3.39 million vehicles registered in the UAE in 2016, where the population was 9.27 million based on the Global Status Report released by the World Health Organization on Road Safety 2018 [8]. The ratio of car ownership and registration is higher in the richer emirates of Dubai and Abu Dhabi. In the Northern Emirate of Dubai, there is one vehicle for every two residents [8].

Therefore, the increment in the number of cars and vehicles in the last decade motivated us to conduct a systematic review on traffic light congestion optimization. This has been reported as one of the most attractive and severe mathematical issues in the optimization fields, due to its high importance in reducing the accident risks, fuel/energy consumption, and decreasing the pollution caused by the emission of CO_2 [9].

The main objective of this systematic review is to conduct in-depth analysis on all research papers published between 1990 and April 2019 that deal with optimizing traffic lights control. We identified from these studies important information such as the available different applications of traffic light signals control and the optimization techniques that were used to enhance the performance of the dynamic traffic light signals. We identified 35 conference and journal papers that used metaheuristic techniques to optimize traffic light control systems. Results showed that about two thirds of the selected papers used genetic algorithm as an optimization technique.

This paper is arranged as follows. Section II demonstrates the related work in the traffic optimization issue. Section III demonstrates background and basic concepts on the traffic signals and traffic lights congestion problems. Section IV describes the methodology followed in conducting this review. Section V lists the main research questions raised in this study. Finally, the paper concludes with Section VI.

II. RELATED WORK

Some Surveys has been presented in the field of traffic control. For instance, Ferreira and d'Orey [1] considered the intelligent transportation systems (ITS) as an optimal solution to solve the environmental problems caused due to traffic congestion. Mainly, the effect of carbon dioxide emission of virtual traffic light (VTL) was evaluated in this survey. The main goal of this survey was to quantify the power of the VTL technology on CO_2 emissions modification. Their evaluations were based on real cities scenario in a complicated simulation framework evaluation including microscopic traffic, emission models and wireless communication. The results of the evaluation were compared with the real physical traffic light system and showed a significant improvement in the traffic flow, accidents were reduced by 30%, and CO_2 emission reduction by 18%.

Warberg et al. [2], presented a comprehensive survey of traffic control with importance of applying the optimization methods. The authors addressed the main conflicts that define the multi-objective traffic signal optimization problem. In this work, two traffic systems were proposed including the DOGS (dynamic optimization of greens co-ordination), and the PP (Phase by Phase). Results showed that DOGS demonstrated a great achievement in optimization. As the only choice to be made for each cycle is whether to shift between traffic-actuated control signal plans or to alternate to a lower or higher capacity program. On the other hand, Phase-by-Phase, reduces the delay utilizing tab search by controlling green time proportions allocated to phases.

Li et al. [10] conducted a survey that aimed to focus on the control side of the traffic lights system. Throughout the survey, different contrasting preferences were discussed. Potentials and drawbacks of the following models were addressed including model-based predictive control versus predictive control models that are based on simulation. The authors concluded in this survey that the potential benefit of intelligent vehicle coordination, in general, cannot reduce traffic congestion when all roads are congested. Further investigations are required to be carried out to estimate the limitations of the performance. Where different problems may occur such as traffic accidents due to the failure of any element in the overall system.

The main contribution of this work is that we conducted a thorough comparison of three popular metaheuristic algorithms: GA, PSO and ACO in the area of traffic control light optimization.

III. Methodology

This systematic review was conducted based on the framework proposed by Kitchenham and Charters [11]. This methodology is characterized by three different and basic platforms (phases), which are; planning, conducting and reporting platforms. In this review, the planning platform included several essential and remarkable points that demonstrate the research questions (RQ) and specifies the searching strategies. Besides, the research strategy was included in the survey and was divided into three sub-stages. The first one is the searching terms, where appropriate and accurate terms were used for our searching process that have a significant contribution in facilitating our searching that will strengthen and reinforce our SLR. The second sub-stage is the survey resources, which shows the different type of online libraries that were used in our searching. The third one is the searching phases.

In this review, we have explained our criteria in including and excluding the collected papers in order to select the appropriate ones. In addition, an evaluation was assigned to each of the collected papers by creating quality evaluation rules. Moreover, the strategy of extracting the data has been clarified. Finally, the extracted data had been synthesized.

A. Research questions

The core objective of this review is to study and conduct a thorough analysis on the research papers that are dedicated to employing the optimization techniques; GA, PSO and ACO to find the best solution to the traffic light signal congestion problems. For example, optimizing the traffic signal timing by taking into consideration to maximize the number of vehicles that are leaving the network. The main essential function is the total timing delay of the traffic light signal that needs to be minimized so that the performance of the road system would be maximized. By minimizing the signal timing, the road performance will be enhanced either in terms of a number of vehicles passing through the signal or in terms of reducing vehicle congestion. According to our objectives, the following four research questions have been raised:

- RQ1: What are the different applications of traffic light signals control?
- RQ2: Which optimization techniques were used to enhance the performance of the dynamic traffic light signals?
- RQ3: What is the impact of optimizing the performance of traffic light networks?
- RQ4: What are the useful tools used in studying the optimization of area traffic control under oversaturated conditions?

B. Search strategy

The following section demonstrates our strategy in the searching process, including the terms that we have used to search the resources that we have utilized to find the suitable articles and our searching phases.

I. Search terms

The searching terms were specified in order to catch and detect the relevant research papers for our topic as much as possible. The formation of the terms was done based on the following procedure:

- The searching terms that has been stated, were extracted according to the research questions from the collected papers.
- The general terms have been replaced by more specific ones (e.g. replace optimization techniques with Genetic Algorithm).
- The terms were replaced by abbreviations (e.g. replace Genetic Algorithm by GA)
- In order to sophisticate our searching results and to make it more accurate, specific and compatible with our survey content, two Boolean-Operators (AND and OR) has been used. We used terms that are related to traffic lights signals and optimization techniques such as “Optimization techniques” AND “Traffic light signals”.

II. Survey resources

The following digital libraries below were used in our searching: Springer, Elsevier, IEEE Explorer, Research Gate, Semantic Scholar, Google Scholar, Academia, SAGE Publishing, Taylor and Francis, INFORMS - Institute for Operations, Research and the Management Sciences, Intech Open, CiteseerX and Wiley-Blackwell.

III. Search phases

The listed libraries above were visited and utilized during the progress of gathering the research papers. The search date was between 1990 and April 2019. We had exposed our collected literature to an inclusion and exclusion test so that the remaining ones will be used in our survey. This criterion is thoroughly explained in the coming sections; therefore, the used papers were limited to 35 publications as shown in Appendix A, Table 3.

C. Study selection

We first started the search terms using the above database libraries and we ended up with 46 papers. After employing the inclusion and exclusion criteria, 35 papers remained. We used the 35 selected papers to compare among different types of optimization methods. Our search, filtering and selection strategy included the steps included below and in Figure 1.

Step 1: Duplicate research papers were removed.
Step 2: choosing only the relevant research papers to our topic by applying inclusion/exclusion criteria.
Step 3: choosing papers with the highest quality by applying the Quality Assessment the best answered our research questions.

a) Inclusion Criteria:

The inclusion criteria used in this systematic literature review includes the following items:

Journals, Conferences, Papers that are related to optimized dynamic traffic light signals, Papers that are related to optimized dynamic traffic lights signals using PSO, Papers that are related to optimized dynamic traffic lights signals using GA, Papers that are related to optimized dynamic traffic lights signals using ACO and Papers that are related to optimized dynamic traffic lights signals using other traditional and non-traditional optimization methods.

a) Exclusion Criteria:

This systematic literature review excludes the following:

- Websites that are non-refereed publications
- Papers that are related to dynamic traffic light signals but do not apply any optimization algorithm.
- Review papers.

IV. Quality assessment rules

The final step in defining the research papers to be included in this SLR review was applying the Quality Assessment Rules. At this stage, we had a closer look at the quality selected papers and examined them more precisely to make sure they precisely support the goals of this survey. The quality of each research paper is calculated based on the QAR's that are set according to our list of research questions. The score of each QAR is set as the following:

- Score = 1 → Fully answered.
- Score = 0.75 → Answered as above average.
- Score = 0.5 → Answered as average.
- Score = 0.25 → Answered as below average.
- Score = 0 → Not answered

We defined 6 QAR's, where each question has a weight of 1 mark out of 6. By calculating the total weight of all 6 questions, we will get the score for each paper. The papers chosen for this SLR are those that scored equal or above 3 out of 6. The QAR's used to evaluate the quality of papers are the following:

1. Is the paper well organized?
2. Is the research objective of the paper clearly mentioned?
3. Is there sufficient background about the topic presented in the paper?
4. Does the paper mention the algorithm used clearly?
5. Does the paper clearly mention the enhancement results of the optimized traffic control lights system?
6. Do the conclusions of the paper match the research objectives?

Table 4, presents the results after applying the Quality Assessment rules, the papers listed in this table are the papers to be used throughout this SLR to present the results to the research questions listed. The papers colored with red have been excluded from the survey as they do not conform to the QAR rules. After applying the quality assessment criteria, the total papers selected were 35 Papers as listed in Table 3 in Appendix A. Out of the 35 papers, 36% were conference papers and 64% were journal papers

V. Data extraction strategy

At this stage of the survey, the data needed to answer the listed research questions are extracted from the finalized papers listed in Table 3. The data that are extracted from the finalized listed papers includes paper ID, paper Title, publication year, publication type, area of traffic control studied, optimization technique(s) used in each paper, RQ1, RQ2, RQ3, RQ4.

VI. Synthesis of extracted data

The extracted information for research results for RQ1, RQ2, and RQ4 are presented in quantitative pie charts and table data that were later used to provide a statistical comparison for each research question. For RQ3, it will be difficult to represent the extracted information in charts or tables. Instead, a descriptive comparison was carried out to provide a comparison of data extracted from the listed research papers.

IV. Results

I. Research Question 1:

The selected papers for these surveys fall under three main categories of applications in traffic lights control for oversaturated areas. Most of the papers worked on the enhancement of the model of congestion around intersections and junctions. However, some papers applied different optimization techniques on real city models (like Alexandria and Toronto) and on some countries (like Turkey), the selected areas of the cities are integration of full model including roundabouts, intersection, and traffic signal lights on streets. Results are presented in Table 1. The category of intersections occupied is approximately 72% of the total selected papers, while city real-life applications occupied around 21% of the papers. On the other hand, applications that concentrated only on roundabouts occupied

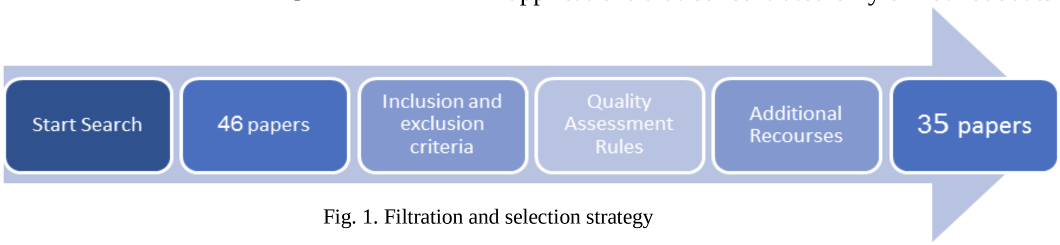

Fig. 1. Filtration and selection strategy

only 7%.

II. Research Question 2:

During our research, we found that the most used recent methods that fall under the category of metaheuristic optimization algorithms are GA, PSO and ACO. Figure 2 shows an approximate percentage of the optimization methods used in the selected papers. From the figure, it is obvious that GA was most used in solving the problem of traffic control. Results also show that hybrid models (using 2 or more techniques together) outperform standalone algorithms. In some previous studies, a comparison between GA and ACO was conducted. The results produced by using the ACO technique in a bigger number of model evaluations demonstrated a huge reduction in the variation amongst a set of random trials. The performance of the ACO surpasses the performance of the GA when they are applied to a large number of models. Therefore, the good choice for solving complex networks is to utilize the ACO technique.

Table 1 Papers categorized as per the application

	application	Number of papers
1	Intersection/junction	"E1, E3, E4, E5, E6, E7, E8, E10, E11, E14, E15, E16, E18, E19, E20, E21, E22, E23, E24, E27, E28, E29, E30, E31, E32, E33, E34, E35"
2	Roundabout	"E16, E26"
3	City real life example	"E2, E9, E12, E13, E17, E25"

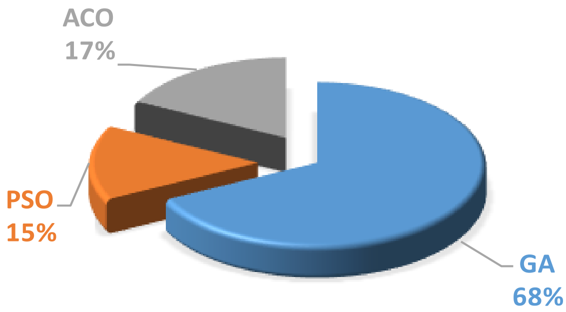

Fig. 2. Algorithms used in the selected papers

III. Research Question 3:

Integrating optimization techniques in the field of traffic lights control had a great impact on the performance. In general, papers that used Genetic Algorithm in its applications [12], [13] has showed a great performance, where the delay reductions were between 13% - 32%. Moreover, Dabiri and Abbas [14] showed that the optimization of traffic lights time decreased the total time of travel compared to when no optimization techniques were used. While the algorithms used in [15], dynamically optimize the red and green times to control the flow of both the vehicles and pedestrians.

Papers that use PSO, also showed a significant improvement. In [16], PSO succeeded to achieve quantitative improvements in both the number of vehicles that reach their destination and the overall journey time. In [17], the improvements showed a decreasing in timings that resulted in 55.9% reduction in average delay time/vehicle that are passing through the roundabout, and an growth of about 9.3% in the total number of vehicles passing through a roundabout / unit time. Applying ACO as an optimization method also showed an enhancement in performance. In [18], according to the stated results, the number of stopped vehicles and the average waiting time at intersections are enhanced.

IV. Research Question 4:

The information extracted from the listed research papers is presented in Table 2. The simulation tools used in the selected research papers MATLAB, VISSIM, and SUMO.

Table 2 Simulation tools used in the selected papers

Simulation tool	Paper's number
Matlab	E21, E11, E26
VISSIM *4.3 simulation**	E4, E27, E11, E26
VISTRO *	E11, E13
SUMO*	E19
ExtendSim simulation*	E20
Microscopic simulation program FLEXSYT-II-*	E23, E35
Microsimulation	E26
Visual Studio 2008 in C#	E30, E11
JAVA	E16, E24
Python	E11
TRANSYT-7F *	E2

"VISSIM 4.3 simulation* A traffic simulation software that simulates all modes of traffic and analyses their interactions.
VISTRO* One of the best optimization models that allow users to build simulation scenarios quickly and offering high computational speed.
SUMO* A well-known traffic simulator that provides an open source, highly portable, and microscopic road traffic simulation tool designed to handle large road scenarios.
ExtendSim simulation* Traffic signal timings under oversaturated conditions
Microscopic simulation program FLEXSYT-II* microscopic simulation program for small scale networks, which can be used to study effects of all kinds of geometric alternatives, like bus lanes, roundabouts, separate left turns, etc.
TRANSYT-7F* Model proposed by Robertson (1969) has been widely recognized as one of the most useful tools in studying the optimization of area traffic control."

V. Conclusions

This paper presented a brief statistical analysis of the use of three metaheuristic algorithms; GA, PSO, and ACO. From the 35 extracted papers, most researchers used genetic algorithm optimization techniques to improve traffic light signal models and to enhance the performance. Such enhancement was through either the number of vehicles passing through the signal, or through reducing vehicle congestion, or time delay. As presented in Figure 9, 68% of the selected papers used GA, while 17% used ACO and 15% used PSO. Traffic light congestion problem is a very broad issue. We recommend authorities to use advanced technologies such as artificial intelligence while designing the traffic lights in order to exploit the ability of the machine learning in anticipating the existence of traffic congestion. This will help in designing smart traffic lights that work based on the congestion occurred and thus minimizing the traffic.

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APPENDIX

Table 3 List of extracted papers

E1	"A Dynamic Vehicular Traffic Control Using Ant Colony And Traffic Light Optimization"	[19]
E2	"A Genetic Algorithm Approach For Optimizing Traffic Control Signals Considering Routing"	[12]
E3	"Rhodes: A Real-Time Traffic Signal Control System: Architecture, Algorithms, And Analysis"	[20]
E4	"A Swarm Intelligent Method For Traffic Light Scheduling: Application To Real Urban Traffic Networks"	[21]
E5	"Advances In Genetic Algorithm Optimization Of Traffic Signals"	[22]
E6	"Agent-Based Traffic Simulation And Traffic Signal Timing Optimization With Gpu"	[23]
E7	"Algorithms For The Traffic Light Setting Problem On The Graph Model*"	[13]
E8	"Ant Colony Algorithm For Traffic Signal Timing Optimization"	[24]
E9	"Ant Colony Optimization Approach For Optimizing Traffic Signal Timings"	[18]
E10	"Applying Genetic Algorithm For Traffic Light Control"	[25]
E11	"Arterial Traffic Signal Optimization Using Particle Swarm Optimization In An Integrated Vissim-Matlab Simulation Environment"	[14]
E12	"Comparing Ant Colony Optimization And Genetic Algorithm Approaches For Solving Traffic Signal Coordination Under Oversaturation Conditions"	[26]
E13	"Genetic Algorithm-Based Optimization Approach And Generic Tool For Calibrating Traffic Microscopic Simulation Parameters"	[27]
E14	"Genetic Algorithm-Based Traffic Lights Timing Optimization And Routes Definition Using Petri Net Model Of Urban Traffic Flow"	[28]
E15	"Multi-Objective Traffic Signal Timing Optimization Using Non-Dominated Sorting Genetic Algorithm"	[29]
E16	"Nested Hybrid Evolutionary Model For Traffic Signal Optimization"	[16]
E17	"Optimal Cycle Program Of Traffic Lights With Particle Swarm Optimization"	[30]
E18	"Optimization Using Simulation Of Traffic Light Signal Timings"	[31]
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