A Bibliometric Review and Analysis of Traffic Lights Optimization*

Gabriela R. Witeck[1] [0000-0002-0131-7347], Ana Maria A. C Rocha[1] [0000–0001–8679–2886], Gonçalo O. Silva[1] [0000–0002–9954–4803], António Silva[1] [0000–0001–7075–3364], Dalila Durães[1] [0000–0002–8313–7023], and José Machado[1] [0000–0003–4121–6169]

[1] Centro ALGORITMI, Department of Production and Systems
University of Minho, Gualtar, 4710-057 Braga, Portugal

gabiwiteck@gmail.com, arocha@dps.uminho.pt,
g.oliveirasilva96@gmail.com, asilva@algoritmi.uminho.pt,
dalila.duraes@algoritmi.uminho.pt, jmac@di.uminho.pt

Abstract. The significant increase in the number of vehicles in urban areas emerges the challenge of urban mobility. Researchers in this area suggest that most daily delays in urban travel times are caused by intersections, which could be reduced if the traffic lights at these intersections were more efficient. The use of simulation for real intersections can be effective in optimizing the cycle times and improving the traffic light timing to coordinate vehicles passing through intersections. From these themes emerge the research questions: How are the existing approaches (optimization techniques and simulation) to managing traffic lights smartly? What kind of data (offline and online) are used for traffic lights optimization? How beneficial is it to propose an optimization approach to the traffic system? This paper aims to answer these questions, carried out through a bibliometric literature review. In total, 93 articles were analyzed. The main findings revealed that the United States and China are the countries with the most studies published in the last ten years. Moreover, Particle Swarm Optimization is a frequently used approach, and there is a tendency for studies to perform optimization of real cases by real-time data, showing that the praxis of smart cities has resorted to smart traffic lights.

Keywords: Traffic lights, Optimization, Smart cities.

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1 Introduction

The significant increase in the number of vehicles on the roads emerges the challenge of urban mobility. Researchers in this area suggest that most daily delays in urban travel times are caused by intersections, which could be reduced if the operation of the traffic lights at those intersections were more efficient. Signalized traffic control significantly reduces vehicle delays at intersections, balances traffic flow, and improves the operational efficiency of an urban street network [1].

In the urban traffic management, the control of the traffic light cycle is fundamental, as its performance directly affects the efficiency of the traffic system, which is controlled by the municipal authorities and its correct installation can improve both traffic flow performance and the safety of all roads users [2]. Due to the characteristics of randomness and complexity of the traffic flow, the traditional light signals working based on a predetermined and predefined clock may not support the actual demand.

Several systems are deployed to control traffic signals, but each system is based on different parameters that can be static (off-line) or dynamic data (real-time). Controlling traffic is not an exhaustive procedure but requires continuous data to be able to continuously function. Many approaches based on different sensors are employed in-vehicle environment perception systems, such as monocular cameras, stereo cameras, and radars. Focusing on the pedestrian and cyclist detection field, vision sensors are preferred, due to the possibility to capture a high-resolution perspective view of the scene with useful color and texture information, compared to active sensors [3]. In this context, optimizing traffic lights may involve implementing the best possible timing settings that control the operation of a traffic signal.

The main objective of traffic signal optimization is to significantly improve the performance of the traffic intersection by minimizing the delay, queue length, the number of stops, and gas emissions. The continuous movement of vehicles generates a huge amount of data that needs to be processed by high-end infrastructure. Recently, optimization approaches have been utilized in traffic control models to increase the performance of traffic signal control systems. Optimizing the transition phase or the shift between the signal timing plans will result in the reduction to its minimum in traveling time, stops, and delays. The positive effects on the environment can lead to a reduction in polluting emissions and fuel consumption. Transition optimization can be an essential way to improve the efficiency of signal systems [4]. Some studies are looking to find out solutions to the problem of congestion, traffic lights, and how to make the process of vehicles on the road safer at a low cost. Thus, emerges a set of research questions regarding the existing approaches to managing traffic lights smartly, the kind of data used, and the benefits of this appliance.

This paper aims to answer three research questions, through a bibliometric literature review. Two important databases (WoS and Scopus) were searched using appropriate keywords to find the most relevant studies on the topic. The outcomes of each research question were discussed.

The paper is organized as follows: Sect. 2 presents the bibliometric review of the literature carried out to support the logic of this study. Section 3 analyzes and discusses the findings of the systematic review research. Finally, Sect. 4 reveals the conclusions and future work.

2 Systematic Literature Review

The research method to carry out a literature review and bibliometric analysis followed four phases [5], which involved the review and evaluation of primary studies relevant to the research. The main is to analyze the state of the art and the current approaches being used in traffic light management using optimization methods, data, and other technologies adopted.

The general process of the proposed study comprises the following steps: (1) Systematic mapping planning; (2) Conduction of the Search; (3) Selection and bibliometric analysis of the primary studies; and (4) Final selection.

2.1 Systematic Mapping Plan

This step consists of two sub-steps: (a) Formulation of the research questions; (b) Selection of the databases and resources.
The research questions (RQ) convey and guide the research directions, as presented below:

RQ1: How are the existing approaches (optimization techniques and simulation) to managing traffic lights smartly?
RQ2: What kind of data (offline and online) was used for traffic lights optimization?
RQ3: How beneficial is it to propose an optimization approach to the traffic system?

The second sub-step is to state the databases and resources. The selection of the databases was based on the content update, availability of the full text of papers, also the quality of the research accuracy. As a result, the database of Scopus and Web of Science (WoS) were eligible. The access to the articles was carried out at Scopus and WoS in the period from 2012 (January) to 2022 (February).

2.2 Conducting the Search

Step 2 aims to define a list of inclusion and exclusion criteria and select appropriate keywords that will be used to find related research work. The list of inclusion and exclusion criteria was established, following the criteria guide to include primary studies that show relevance to the research questions and exclude the studies that do not show relevance to answering the RQ.

The criteria are:

- Exclusion criteria (EC)

EC1: The study is not written in the English language.
EC2: The Full-text paper is not available.
EC3: The research does not cover the topic of smart cities.
EC4: The document type is not a Conference Paper, Article, Review, Proceedings Paper, or Article in Press.

- Inclusion criteria (IC)
  IC1: The study aims to reduce traffic congestion and delay time.
  IC2: The study is looking for road safety and traffic forecast topics.

Based on the carefully selected keywords (traffic light, optimization, data, smart or intelligent) the database strings must be followed to search the proper databases Web of Science (WOS) and Scopus. Additionally, the search string followed the format: TITLE-ABS-KEY ("traffic light*") AND TITLE-ABS-KEY (optimization) AND TITLE-ABS-KEY (data) AND TITLE-ABS-KEY (smart OR intelligent).

2.3 Selection and Bibliometric Analysis of the Primary Studies

As a result of applying the criteria established in Step 1, the researchers have identified 157 studies. In this step, it was used an open-source scientometric tool called ScientoPy [6]. This tool is a Python script-based tool specialized in temporal scientometric analysis.

Later, the document types, not relevant (EC4), and repeated studies within the databases were eliminated. The papers published in WOS were maintained, and those that were in Scopus were subtracted. In total resulted 93 papers in this phase, see Table 1.

Table 1. Documents uploaded.

Information	Number	Percentage
Total papers uploaded	**157**	
Document type removed – EC4	22	14.0%
Total papers after papers removed	**135**	
Loaded papers from WoS	66	48.9%
Loaded papers from Scopus	69	51.1%
Removed duplicated papers from Scopus	42	60.9%
Total papers after the removal process	**93**	
Papers from WoS	66	71.0%
Papers from Scopus	27	29.0%

Figure 1 shows the pre-process brief graph, that presents the loaded documents for each database and the removed duplicated documents, respectively. Since ScientoPy preprocess script keeps WoS documents over Scopus documents, after the duplication removal filter we see more documents from WoS than the Scopus database [6].

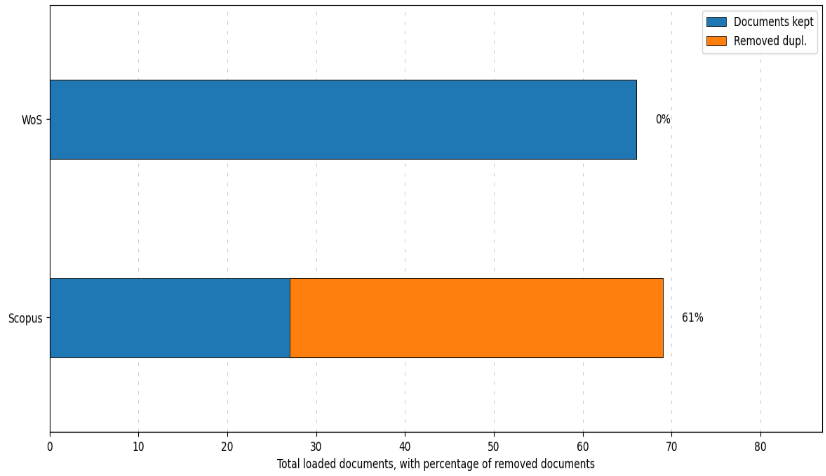

Fig. 1. Loaded and removed documents for each database.

After completing the search phase, the source documents were categorized by several publications considering their type: articles, proceedings papers, conference papers, and reviews (see Fig. 2).

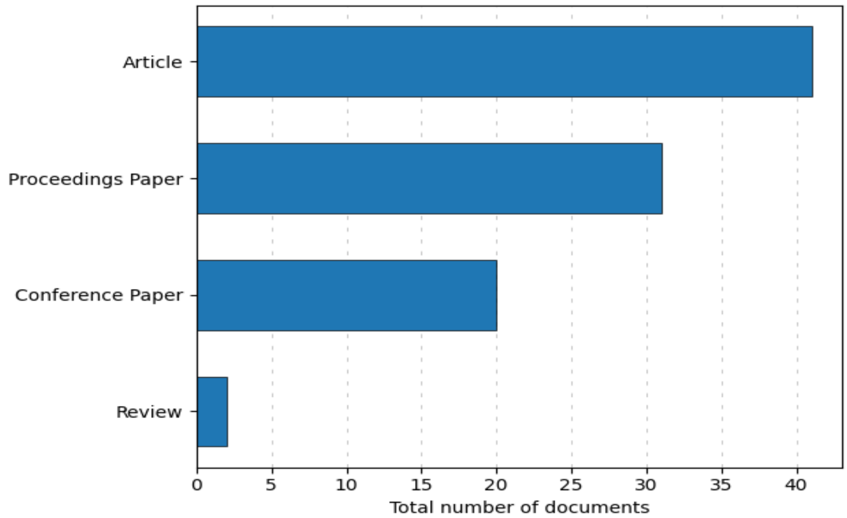

Fig. 2. The number of documents per type.

The author's keywords are shown in Fig. 3 as a word cloud visual representation, where the size of the word or phrase is proportional to the number of documents related to it.

The word cloud highlighted the principal topics that are using the optimization related to traffic lights, like intelligent transportation systems and traffic congestion.

Fig. 3. Word cloud for author´s keyword.

All source documents were then linked to authors by their full names, publication year, and country. Figure 4 details the number of publications by Country in recent years. The figure on the left reveals that the United States and China were the countries with the most studies published in the last ten years. On the other hand, the figure on the right side shows the percentage of documents published in the last two years when compared to the average number of published documents in the last 10 years.

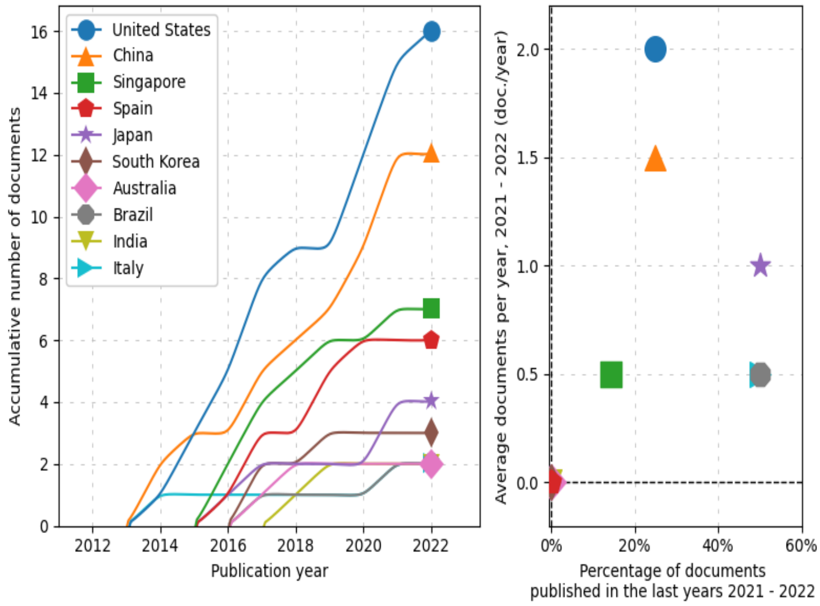

Fig. 4. Documents published per country and year.

After the bibliometric analysis of the results obtained in Step 3, it was necessary to nominate “Basic terms”, or keywords, to analyze all the 93 papers found until this step. The terms must be simple and meaningful enough to cover the Research Questions, which can bring back more accurate results in the searched databases. Table 2 shows a list of all nominated keywords.

Table 2. Basic terms for each research question.

Research Question	Basic terms
RQ1: How are the existing approaches (optimization techniques and simulation) to managing traffic lights smartly	Optimization, techniques, simulation, methods, tools, simulator, algorithm, system, transport management, traffic monitoring, smart traffic
RQ2: What kind of data (offline and online) was used for traffic lights optimization?	Online, offline, real, virtual
RQ3: How beneficial is it to propose an integrated smart approach that uses online traffic data to detect cyclists, cars, and pedestrians	Results, cyclists, pedestrians, motorized vehicles, road users, benefits, impact, outcome, method, reach, safety, a passerby

2.4 Final Selection

The 93 papers were forwarded to the final selection process. In this step, if the full-text paper was not available (attending the EC2) it will not be considered. This criterion excluded 25 papers.

Then, a total number of 68 paper abstracts were screened. The researchers have reduced the total number of references found by their abstract relevance. The abstract was read and then determined whether the paper is related to the study or not. Therefore, 29 papers were not related to the study. This step follows immediately after abstract screening, which indicates if the abstract is related, and papers received one more screening by reading the full text to determine its relevance. Finally, a total number of 39 papers were reviewed in detail. Table 4 shows the screening and selection process.

Table 4. Papers screened and analyzed

Information	Number
Papers after Step 2	**93**
Papers with full-text not available (EC2)	25
Total papers abstract screened	**68**
Paper not related to the study	29
Total paper full-text screened and analyzed	**39**

3 Results and Discussion

In this section, the total number of 39 papers was reviewed in detail. The papers were studied, and applied the search for “Basic terms”, as above mentioned in Table 2. It identified the answers to the research questions.

The RQ1 raised the question regarding the existing approaches to managing traffic lights smartly and it was possible to find many approaches in this matter. It was identified 24 different technologies and algorithms applied to traffic lights optimization, as shown in Table 5.

Among the optimization approaches found in the literature, the ones that have been widely used in traffic light optimization are the Discrete harmony search [7, 8], Genetic Algorithm [9], and Particle Swarm Optimization [10, 11]. The main objective of the optimization approach is to find out an optimal solution for the traffic light problem.

Table 5. Summary of the technologies and algorithms

RQ1	
Algorithmic game theory (AGT)	Jaya Algorithm
Ant colony optimization (ACO)	Module VisVAP
Artificial bee colony (ABC)	Nearest neighbor (NN)
Breakdown minimization Principle (BMP)	Novel framework dynamic TL control
Cell Transmission Model (CTM)	Particle Swarm optimization
Cellular Genetic Algorithm (CGA)	Proximal Policy Optimization (PPO)
Discrete harmony search (DHS)	Traffic Actuated Optimization Signal Fuzzy control (TAOSF)
Edge for traffic light control (DRLE)	Traffic Actuated Signal Fuzzy Control (TASFC)
Faster R-CNN	VANET
Harmony search (HS)	Wardrop’s user Equilibrium (WE)
Intelligent signal light timing model principle	Water cycle algorithm (WCA)
Intelligent traffic signal optimization control platform	YOLO

In traffic light optimization, it is also common to apply a simulator, which makes it easy to compare the algorithms on different infrastructures and traffic patterns. The simulations of the results could be found in seven: AIMSUM simulator, Java-Agent-Development-Environment (JADE), MATLAB, Netlogo, NS2, PTV Vissim, and SUMO. The last one (SUMO) was the most used simulator, and it is an open-source traffic simulation package including net import and demand modeling components. The Participle Swarm optimization, a stochastic global optimization method that takes inspiration from the social behaviors of insects and other animals, was the most used.

In [12], a multi-agent-multi-purpose system (MAMP) to solve the traffic light problem was developed, where an ant colony optimization (ACO), by a distributed intelligent traffic system (DITS). The results have shown that for several initial distributions of vehicles, the ACO strategy obtains higher average speeds, smaller average waiting times, and several stopped vehicles than the non-ACO strategy. The application of the ACO combined with the SUMO traffic simulator was also used in [13]. This work confirmed a better performance of the developed algorithm compared to the predefined time controller and other dynamic controllers. Moreover, in the work [14] the Harmony Search (HS) and artificial bee colonies (ABC) to solve the urban traffic light scheduling problem were implemented. The offline data were based on the real traffic in the Jurong area of Singapore. The authors aimed to minimize the total network-wide delay time of all vehicles and the total delay time of all pedestrians at the same time.

The work in [15] mentions that future optimization algorithms for the traffic light scheduling problem should consider the reliability of solutions over multiple traffic scenarios and incorporate simulation strategies that improve reliability. However, the highly dynamic traffic of a city means that no single traffic scenario is a precise representation of the real system, and the fitness of any candidate solution (traffic-light program) will vary when deployed in the city [15].

Managing smart traffic lights can be done by using different approaches and techniques. Furthermore, to perform the optimization and find the optimal values of the traffic light cycle time, some programming languages can be applied, in this study identified two of them: are Phyton and CC++.

To answer the RQ2, the study revealed 18 papers using off-line data, and 21 using real-time data. However, all of them use data from real cases, showing that the praxis of smart cities has resorted to smart traffic lights. The global optimization of traffic-light problems has been applied in smart city case studies when the real-time control of traffic lights is not possible. It requires the optimization and simulation of a traffic scenario that is estimated after collecting data from sensors at the street level.

Although several traffic flows forecasting techniques have been developed and have achieved good forecasting performance, the author´s papers are separate from traffic light control research. In other words, existing studies focus on traffic light optimization or traffic flow prediction, but few studies combine these two techniques. To consider the effect of traffic light control over a period, the expected traffic condition must also be considered.

Eight out of 39 papers presented answers to the RQ3, showing the benefit of using an optimization approach for the traffic light system. Even though the answers did not cover the entire expected content. The respective papers and answers are revealed in Table 6. In general, the results confirm an increase in the overall performance of the system when the application of optimization approaches is introduced. However, most articles do not quantitatively present the results, but only in a qualitative way.

The RQ3 was also focused on looking for papers and solutions by designing a system which is considering both types of road users, motorized vehicles, and cyclists. However, the papers studied had no attention to cyclists in the initial traffic signalization planning. Bicycle traffic and user roads have not been given the same priority as motorized traffic.

Table 6. Papers and questions research

Papers	RQ1	RQ2	RQ3
[16]	Particle Swarm optimization, SUMO, VANET	Off-line	The model saves time up to 57% compared to the static plan and in dense traffic conditions with high traffic intensity.
[9]	Genetic algorithm, simulator AIMSUM	Off-line	The proposed active control of traffic lights could reduce by half the average delay time needed for vehicles to cross the region under study.
[17]	Jaya algorithm, harmony search, and water cycle algorithm	Real-time	Improvement ranges from over 26% and 28% in terms of the minimum and maximum total delay times.
[18]	Cell Transmission Model, SUMO	Real-time	The algorithm provides near-optimal solutions with a maximum optimality gap of 5.4%.
[19]	Decentralized Reinforcement Learning at the Edge for traffic light control in the IoV (DRLE)	Real-time	DRLE decreases the convergence time by 65.66% compared to PPO and training steps by 79.44% compared to ARS and ES.
[20]	Ant Colony Optimization, SUMO, VANET	Real-time	20-25% improvement in delays. Decrease of 14-18% in CO emissions, 15-21% fuel consumption, 7-9% noise rate.
[21]	Intelligent traffic signal optimization control platform	Real-time	The overall total delay time was reduced by 23%, and the travel time was reduced by 15%

4 Conclusions

The number of vehicles has been increasing more and more in urban areas, so the challenge of urban mobility is emerging. The literature in this area suggests that most daily delays in urban travel times are caused by intersections, which could be reduced if traffic lights (in these intersections) were more efficient. Using traffic light simulation to coordinate vehicles passing through intersections can be an effective and efficient strategy when combined with the optimization of traffic light cycle times.

This research aimed to improve the understanding of traffic light management using a bibliometric literature review. Two important databases (WoS and Scopus) were searched using appropriate keywords and started narrowing down to find the most relevant studies based on a clear process of screening the papers. The results of this process culminated in the selection of 39 articles that were within the smart cities area and had the full text available. The outcomes of each research question were clearly discussed.

The bibliometric research revealed that the United States and China were the countries with the most studies published in the last ten years, and the most common document type of publication is articles and proceedings papers.

Later, the selected studies showed 24 existing technologies and algorithms. The results confirm a performance increase in the system with the application of optimization approaches. From these, 18 papers used offline data, and 21 papers used real-time data. But all of them are data from real cases, showing that the praxis of smart cities has resorted to smart traffic lights.

The state-of-the-art in traffic control relies on integrating information technology into traffic systems, referred to as ITS. Such systems usually require investments and work time to upgrade the existing traffic infrastructure by integrating sensors and traffic facilities. Moreover, the papers studied had no attention to cyclists and pedestrians in the initial traffic signalization planning, i.e., bicycle traffic and users' roads have not been given the same priority as motorized traffic.

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