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Traffic light control design approaches: a systematic literature review

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ABSTRACT

To assess different approaches to traffic light control design, a systematic literature review was conducted, covering publications from 2006 to 2020. The review's aim was to gather and examine all studies that looked at road traffic and congestion issues. As well, it aims to extract and analyze protruding techniques from selected research articles in order to provide researchers and practitioners with recommendations and solutions. The research approach has placed a strong emphasis on planning, performing the analysis, and reporting the results. According to the results of the study, there has yet to be developed a specific design that senses road traffic and provides intelligent solutions. Dynamic time intervals, learning capability, emergency priority management, and intelligent functionality are all missing from the conventional design approach. While learning skills in the adaptive self-organization strategy were missed. Nonetheless, the vast majority of intelligent design approach papers lacked intelligent fear tires and learning abilities.

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1. INTRODUCTION

Increased population density contributes to an increase in the number of vehicles on the route, resulting in traffic jams. While there are traffic rules and laws in place to ensure that road users drive in a user-friendly manner that accommodates all drivers, ensuring that traffic flows smoothly are not a simple job. Lights are the signaling systems that are used to direct traffic on a multi-way lane. These are positioned to prevent accidents by controlling the opposing movement of traffic at road intersections. Despite the fact that traffic light operation has been studied for decades, the current system is based on outdated assumptions and is rapidly becoming obsolete. When changing traffic light signals, both speed and the number of cars on the road must be taken into account; otherwise, the device would lose phase and become unsynchronized.

This paper presents a systematic literature review (SLR) of research efforts on traffic light control (TLC) architecture approaches from 2006 to 2020. The SLR starts by agreeing on the basic requirements, after which a total of 145 papers were deemed acceptable. The total number of studies has been reduced to 52 after redundant studies were removed. Finally, only 39 papers are thoroughly examined. After extensive study and analysis, the desired knowledge was extracted from these documents.

The following is a description of the structure of the paper. The principles of traffic light management design are first thoroughly investigated. After that, there's a synopsis of the study's related work. In the third part, the research method was extensively discussed. In the results portion, the findings were extensively discussed. The study concluded with a discussion of the research findings and limitations.

2. DESIGN APPORACHES' RELATED WORK

Several scholars have published surveys and reviews on traffic light control architecture [1]–[3]. Despite this, their study survey works lack specific information about the advantages and disadvantages of each strategy. Wang *et al*. [3], for example, published a review article on self-adaptive traffic signals that looks at the advancement of commonly used self-adaptive signal control systems around the world. The research survey was focused on self-adaptive approach only which consider to be as limitation. Shinde and Jagtap [4] Summarizes an analysis of the different approaches used in the implementation of an intelligent traffic management system. This paper provides a concise comparison of all the approaches, as well as the benefits and drawbacks of each.

In research [5], Kotwal *et al.* examines and synthesizes data on a broad range of signal systems, detection devices, and communications elements in order to provide a comprehensive understanding of current technology in the United States. Current signal system practices were examined in order to compare emerging technologies and to investigate postmodern technologies. Recommendations for further investigation of traffic signal systems were also provided. While research [6] summarizes a study of various methods for creating an intelligent traffic detection algorithm based on the references to various research articles. It also includes a study of various image processing methods for designing an intelligent traffic system. Souza *et al.* [7] published an article on the current traffic management system, which included a classification, analysis, problems, and possible perspectives. Nevertheless, Jensen *et al.* in [8] presents the challenges that researchers must overcome in traffic light recognition research and provides an overview of ongoing work. The aim is to elucidate which areas have been thoroughly researched and which have not, thereby uncovering opportunities for further improvement.

Hawi *et al.* [9] has written a paper that examines the reasons behind the creation of various types of traffic management systems currently in use. Fuzzy expert systems, artificial neural networks (ANN), and wireless sensor networks are among them. Each technique is examined in detail, including its architecture, benefits, and drawbacks. The findings of a comparative analysis were examined. As a result, the majority of available research works on traffic light control architecture were extensively reviewed in this paper. Furthermore, the study is divided into three sections: i) conventional design approach, ii) self-organizing and adaptive design approach, and iii) intelligent design approach.

2.1. Conventional design approach

Sharma *et al.* [10] suggested an fine-pitch ball grid array (FBGA) based traffic light controller architecture. In comparison to other design methods, the author believed that using FPGA minimized power consumption. In addition, the overall power consumption of traditional traffic light controllers was calculated as a function of the logic circuit's operation frequencies. Meanwhile, Pujithsai *et al.* [11] suggested an ultrasonic sensor and microcontroller-based TLC system. The key contribution was the allocation of green and red-light times depending on the density of traffic around them. Despite this, Sabri *et al.* [12] proposed a system for controlling access to areas shared by several intersections. A disadvantage of the proposed solution was the absence of pedestrian crossing lights. Osigbemeh *et al.* [13] proposes a major halogen lamp-based energy-saving system. Nonetheless, Zhou and Yang [2] suggests an FPGA-based traffic light control system. The proposed system traffic lights control was divided into seven parts after analyzing general design requirements.

Apart from the aforementioned reports, Usikalu *et al.* [14] claimed to have developed novel device systems using an Arduino and the Arduino integrated development environment. It allows traffic lights to offer priority access to roads with a large number of vehicles. However, the claimed work lacks the capacity to manage a large-scale deployment to all roads with heavy traffic congestion.

El-Medany and Hussain [15] implements a low-cost advanced traffic light controller system based on a very large-scale integration (VLSI) architecture. While Qi *et al.* [16] uses deterministic and stochastic Petri nets to construct an emergency traffic-light control scheme. Nevertheless, Jaiswal *et al.* in [17] present a novel, low-cost technique to control 8-way/6-way traffic light system based on microcontroller. The system operates with traffic lights implemented with light-emitting diode (LED) technology. System tries to reduce possibilities of traffic jam, caused by overcrowd, to an extent.

Apart from that, Batishcheva and Ganichev [18] proposed a system that offered several parameters to improve safety of complex road junctions, including use of redundant road markings. The developed system will allow reducing accident risks and improving traffic safety; as being claimed. However, Reyes-Muñoz *et al.* in [19] proposed an article that investigated two features, namely: i) an exhaustive review of the current mechanisms to detect four basic physiological behavior states that may cause traffic accidents is presented and ii) a middleware architecture is proposed.

The paper presents by Nellore and Hancke [20] offered an approach that gives priority to emergency vehicles. The distance between the emergency vehicle and the intersection is calculated by using a Euclidean

distance, Manhattan distance, and Canberra distance techniques. Kokate *et al.* [21] suggested a scheme that helps to reduce ambulance delays. Developed a website called "HealthCard" to enable people to register their medical histories. The information will assist in reducing the amount of time spent in the hospital preparing for care. Using a unique id and fingerprint verification, this data can be retrieved. Hashim, on the other hand, proposes in [22] a device that responds automatically when it receives a signal from an emergency vehicle.

2.2. Intelligent design approach

Ghazal *et al.* [23] proposes a device that can estimate traffic density using infrared sensors placed on either side of the lane. It is regulated by a microcontroller. Nonetheless, Rotake and Karmore [24] created a method that used a genetic algorithm to estimate unknown traffic volumes. Simplicity is regarded as a disadvantage. Lee and Chiu [25] suggested a smart traffic signal control scheme, which is worth mentioning. Emergency vehicle signal preemption, public transportation signal priority, adaptive traffic signal management, eco-driving service, and message broadcasting were all enabled by the system.

Xu *et al.* [26] proposes a novel decentralized multi-agent scheme for massive traffic light coordination to facilitate large-scale green transportation. The findings of a local intersection and its neighbors were used as evidence to support traffic light synchronization decisions in this approach. Thakare *et al.* [27] proposes a dynamic time interval traffic light system based on the length of presented vehicles in each lane. In addition, it prioritizes emergency vehicles. While, Mainali *et al.* [28] proposes a genetic algorithm for estimating traffic volume in road sections. Furthermore, it is capable of predicting traffic level.

Furthermore, Chavan *et al.* [29] traffic light controller solves a big issue with traditional traffic signals. A genetic algorithm was used in the proposed scheme. As a result, Salama *et al.* [30] proposes an integrated intelligent traffic light system based on photoelectric sensors distributed along roads. This approach is ineffective and nearly always results in traffic congestion during rush hour. While, a traffic light will decide itself the timing based on the current traffic density is proposed by Zubillaga *et al.* [31]. Nevertheless, Atta *et al.* [32] proposed an intelligent system that can maintain the dynamic timings of traffic signals by sensing the density of traffic to minimize the congestion with the help of internet of things (IoT) enabled sensors which provides the advanced and powerful communication technologies for the citizens. Yet, Albagul *et al.* [33] developed a system that is able to sense the presence or absence of vehicles within a certain range by setting the appropriate duration for the traffic signals to react accordingly.

Alothman in [34] proposes a new intelligent traffic control (ITC) system. The proposed ITC system is designed as a dynamic system by using a fuzzy expert system; the fuzzy rules are applied in the visual basic and computer-based program (excel) to run the validation process. The developed control system applied on five intersections in the grid network at four periods. Kapitanov *et al.* [35] published an article that consist of two basic approaches to development of network mathematical models of traffic flows, based on a set of analytical models and on micro level simulation models.

While another system proposal that drafted by Dabahde and Kshirsagar [36] which makes use of FPGA technology along with traffic sensors to control traffic according to the traffic requirement and thus reduces the waiting time, at an intersection of two roads. A technique that use a sensor network and embedded system is proposed by Ambekar *et al.* [37]. The timings of traffic lights will be decided based on the total traffic on all adjacent roads.

Saradha *et al.* in [1] develop an application that will provide a "Green Corridor" to the ambulance. The project consisted of four modules; namely: i) admin module, ii) ambulance user, iii) global positioning system (GPS) tracking, and iv) signal manipulation. The use of GPS tracking will help to locate the ambulance and its position also it will reduce the bulkiness of the project. As soon the system gets the request, the admin will send the driver to the location with route provided by him and also will be able to track the ambulance.

Sin's research aims to create a new traffic light system that combines machine learning with object detection and analysis using an evolutionary algorithm. This is to implement a real-time strategic signal switching arrangement at intersections in order to reduce pedestrian and vehicle waiting times and improve road users' travel experiences [38]. Due to congested driving conditions, emergency vehicles such as rescue vehicles, fire units, and squad cars face several challenges in achieving their objectives, resulting in the loss of human lives. To address this issue, Kulkarni and Ade [39] propose a new concept that uses a variety of radio frequency identification (RFID) labels in this system to distinguish between the rescue vehicle and the stolen vehicle.

2.3. Self-organizing, and adaptive design approaches

Works relating to adaptive self-organization models were evaluated and contrasted in this section. Djuana *et al.* [40] introduces a research project in which he develops an adaptive traffic light control system as part of a smart system for improving road use and minimizing congestion. Three research problems are the subject of this study: i) congestion in one direction toward an intersection due to dynamic traffic conditions,

while traffic light timing cycles are mostly static, ii) no timing synchronization among traffic lights in adjacent intersections, resulting in unsteady flows, and iii) difficulties in traffic condition monitoring on one intersection and a lack of facility for remote controlling of traffic lights. A system that ues an infrared sensors with an embedded microcontroller chip is proposed by Udoakah and Okure [41]. The design needs to be modified to control more than four lanes of traffic.

Cools *et al.* [42] design a realistic simulation for self-organizing traffic lights. It aims to reduce waiting time and traffic jams in the traffic light. The proposed research methodology is mainly states that each traffic light keeps a counter which is set to zero when the light turns red and then incremented by the number of cars approaching only the red light.

A model that used an exclusively elementary cellular automata is proposed by Gershenson and Rosenblueth [43]. It does not considered in the simulations turning vehicles. While, a self-organizing method that build based on cyclic boundaries, and non-orientable boundaries is proposed by Zubillaga *et al.* in [31]. Furthermore, show that the measures are useful to identify and characterize different dynamical phases. Nevertheless, an approach that used sensors to achieve self-organizing traffic light coordination is proposed by Zapotecatl *et al.* [44]. The simulated results showed a superior performance over a traditional method. While, a design of a real-time traffic light control system that based on FPGA is proposed by [45]. The claimed results and genunity was proved by simulation only. The system is mainly relies on installing ground sensors to calculate the volume of traffic density.

The Gershenson [46] author of self-organization traffic lights approach claimed that this approach is an adaptive method. In other words, information feedback between elements, that in turn helps mediate the interaction in achieving the global adaptive task. Nevertheless, shows a highly sensitive to changes that occur in traffic environment in terms of car volume and adaptiveness response. SIVA in [32] proposed an implementation of new technologies in automating traffic flow in road construction site could possibly eliminate the usage of a conventional flagman at all times.

Geetha claimed design of an intelligent auto traffic signal control system [47]. The proposed system tries to minimize the possibilities of traffic jams, caused by the traffic lights, to some extent by clearing the road with higher density of vehicles and also provides the clearance for the emergency vehicle if any. John proposes a regional traffic control system that can detect incident situations and provide coordinated traffic management during non-recurrent congestion events in his paper [48]. Advanced artificial intelligence (AI) techniques are combined with a traffic performance model based on highway capacity manual (HCM) equations in this framework.

3. RESEARCH METHOD

The research method section is mainly emphasis on planning, conducting the review and reporting the results. First author formulates and define research questions related to the students learning readiness on the embedded system design. Second, author search for relevant literature through various databases and extract related facts. Finally, author write a report of the systematic review findings.

3.1. Research questions (RQs)

The first step in conducting a systematic review is to determine the study questions. This move must be brief and straightforward. The following are the research questions in the context of this study: i) RQ What is the status of TLC research right now?, ii) RQ What are the most powerful methods for creating TLC?, and iii) RQ What are the most important holes and shortcomings in the studies that have been reviewed?.

3.2. Defining search strategy

The targeted search strategy of this review included determining the population, selecting resources, deriving search strings, and the inclusion and exclusion criteria. The study keywords had been determined from the research questions. The chosen keywords were double-checked with the study research questions so as to ensure that they were indeed aligned with the research objectives and expectations; as shown in Table 1. The search string displayed in Table 2 was applied to implement search on the five selected online databases using Boolean operators to identify the primary articles.

Table 1. Search keywords

Traffic Light Control	Approach, and features
Road traffic	Technique, and outcomes
Adaptive traffic system	Self-adaptive and self-organizing
Intelligent traffic	Smart traffic, and management

Table 2. Search string

Main search string
["Traffic &Light& System" OR "Road traffic management" OR "Adaptive traffic system" OR "intelligent traffic" OR "self-organizing road traffic"]

3.3. Conducting review process

This section describes the actual implementation of the review. As such, the preferred reporting items for systematic reviews had been applied to carry out the review based on the defined protocol illustrated in Figure 1. The process involved identification of research pilot search, and selection of study.

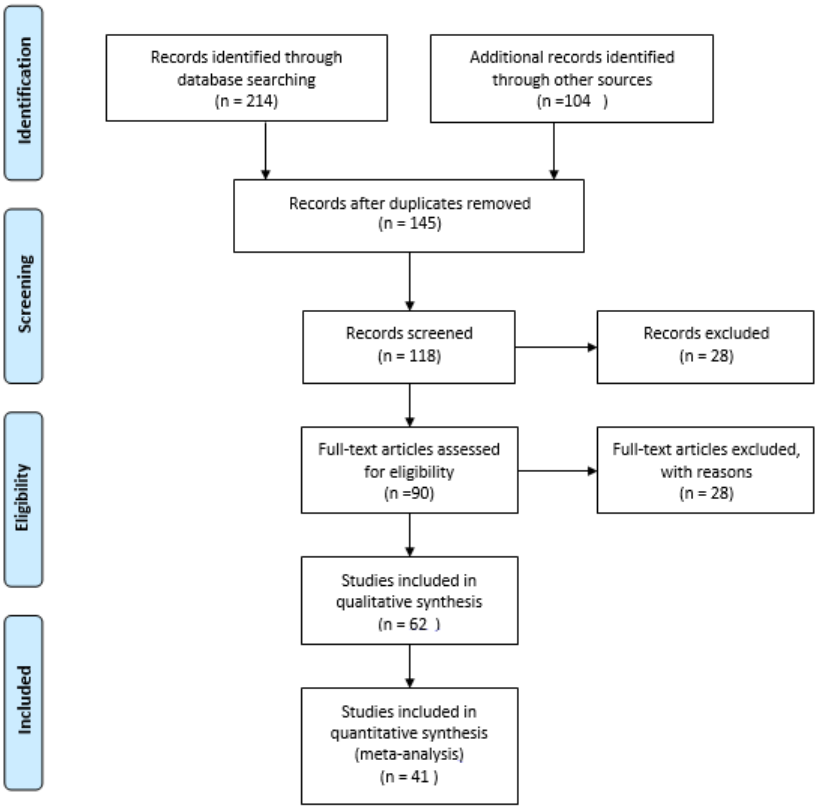

Figure 1. Search strategy

4. RESEARCH FINDINGS

4.1. Answering the research questions

This section summarizes and discusses the answers to the research questions. The relevant articles from the data extracted in the data extraction form had been used to answer each RQ, as shown in Table 3. As mentioned, In this research paper the systematic literature review (SLR) was performed, instead of the common literature review, mainly due to its high scientific value that is comprised of a sound and predefined search approach, as well as excellence evaluation criteria, which is absent in literature review, and any chance of missing article is less possible, when compared to the literature review [49]. Other than that, [50] managed to list three reasons for the implementation of a systematic literature, which are: i) to summarize the existing evidence concerning a treatment or a technology, e.g. to summarize the empirical evidence of both benefits and limitations of a specific agile method, ii) to identify any gap in the present research in order to suggest areas for further investigation, and iii) to provide a framework or background to appropriately position new research activities. Nevertheless, this study performed the SLR based on the guidelines provided by Rycroft *et al.* [50], where articles from varied database sources were explored using predefined keywords to gather relevant research materials so as to answer the outlined research questions [51].

RQ1. What is the status of TLC research right now? The current state of researchers was the subject of this research issue, which was conducted between 2006 and 2020. In particular, 39 papers were carefully examined and chosen from a total of 145, as shown in Table 3. RQ2. What are the most powerful methods

for creating TLC? The researchers' most successful techniques were the subject of this research issue. Table 4 shows the three groups that were discovered. A total of 14 of the 39 papers were listed as using a conventional design approach. Furthermore, 16 of the 39 articles were classified as intelligent design method papers. Finally, 9 of the 39 participants focused on self-organizing and adaptive design. RQ3. What are the most important holes and shortcomings in the studies that have been reviewed? The emphasis of this research question is on recent shortcomings and gaps. The conventional design approach examined papers omitted many features that were deemed to be gaps and weaknesses, including: i) versatile time span, ii) learning capacity, and iii) priority for emergency vehicles. Although the reviewed papers' intelligent design approach had the following flaws: i) dynamic time interval, ii) learning capacity, iii) emergency priority management, and iv) intelligent functionality. Nonetheless, the following weaknesses were identified in the collected and checked papers that covered self-organizing and adaptive design approaches: i) dynamic time interval, ii) emergency vehicle management, iii) knowledge given to users, and iv) intelligent features.

Table 3. Studies relevance to research questions

RQ No.	No. of Studies
RQ1	41
RQ2	41
RQ3	30

Table 4. Summary of RQ3 findings

Approach	Article number	Offered Features			
		Flexible time	Emergency priority	Learning ability	Intelligent features
Conventional	[10]–[15][16]–[23]	No	No	No	No
Self-Organizing	[33], [43]–[46]	Yes	No	No	No
and adaptive	[52]	No	Yes	No	No
Intelligence	[25], [32]	No	Yes	No	No
design	[26]	No	No	Yes	No
	[29], [39], [40]	Yes	Yes	No	No
	[24], [28], [30], [31], [34], [35]	Yes	No	No	No
	[1], [9], [36]–[38], [41]	No	No	No	No

4.2. Results discussion

However, none of the aforementioned papers have addressed any of the requested features, namely: i) dynamic time allocation, ii) priority for emergency vehicles, iii) learning capability for drivers and traffic controllers, and iv) intelligent features, nor have they provided an ideal solution for current TLC issues. As a result, this paper analyzed the vast majority of available research works on traffic light control architecture. During the last two decades, the conventional design approach has been thoroughly researched. i) complex time interval, ii) learning capability, iii) emergency priority management, and iv) intelligent functionality are all lacking in this approach. Consequently, adaptive self-organization models were tested, analyzed, and compared in this study. The papers reviewed in this method lack i) learning capabilities for drivers and traffic controllers, as well as and ii) intelligent functionality, and they have not offered an ideal solution for current TLC issues. The vast majority of intelligent design approach papers do not have learning ability or intelligent fear tires, as alleged. It is worth noting that only one of Lee and Chiu's research papers [25] has a learning potential and lacks intelligent features. Nevertheless, in the event of a medical emergency, Rajak and Kushwaha [52] suggests a proposal for a centralized traffic control system that can provide a "Green Corridor" for an ambulance. To identify the car, the device employs IoT and RFID techniques.

5. DISCUSSION AND FUTURE RESEARCH

5.1. Research discussion

The aim of this research was to undertake a systematic literature review that covered research from 2006 to 2020. In particular, it is to extract and analyze protruding techniques from selected research articles in order to provide researchers and practitioners with recommendations and solutions. This systematic literature review was conducted to determine various traffic light control design approaches. The study will be undertaken with the aim of gathering and investigating all studies that have looked at road traffic and congestion issues. The focus of the research methodology was on preparing, conducting the analysis, and reporting the findings. According to the results, there has yet to be a specific design that senses traffic and provides intelligent solutions.

5.2. Research limitations and recommendations for future research

Since research is a never-ending operation, this section details the study's limitations and restrictions, which may have an impact on the overall results and encourage other researchers to conduct additional research. The study's aim was to figure out what design methods are currently in use for TLC design. This was accomplished by conducting a systematic search of the ScienceDirect, Scopus, Web of Science, Emerald, and Google Scholar databases, which included only papers written in English. Thus, there might be other relevant research papers omitted as it was published in language other than English language.

Through SLR, it is obvious that TLC still needs more research. According to the research findings, there is no research on developing TLC with intelligent features and learning abilities. Furthermore, the study shows a lack of research into designing new systems that are suitable for today's high demand for addressing traffic congestion. Researchers are invited to participate in this ongoing study.

Artificial intelligence (AI) and machine learning (ML) are now playing an increasingly important role in solving a wide range of real-world issues. As a result, current traffic light systems need modern, innovative design approaches that include the following features; namely: i) detecting and analyzing objects or vehicles by using machine learning; ii) the average waiting time for pedestrians and vehicles should be dynamically, optimized, resulting in improved road use and thereby alleviating the congestion problem, iii) ambulances and firefighting vehicles should be given automatic priority, and iv) road users and motors should have the opportunity to understand and learn from the accumulated data.

The behavior of learning traffic light controllers is currently being studied by the author on a variety of infrastructures. In addition, it is intended to adapt the planned framework to real-world traffic situations. Modern technology, such as communicating networks, can be used on a wide scale to achieve this, allowing for the required connectivity between road users and traffic lights. As a result, the author urges future researchers to conduct additional research and look at the use of machine learning and communication networks in the creation of more autonomous and intelligent traffic control systems.

6. CONCLUSION

The conventional design methodology has been extensively researched over the last two decades. This approach lacks i) complex time intervals, ii) learning capability, iii) emergency priority management, and iv) intelligent features. While adaptive self-organization approach papers were examined in this approach, they lacked: i) learning capabilities for drivers and traffic controllers, as well as and ii) intelligent features, and they failed to provide an ideal solution to current TLC issues. Nevertheless, the vast majority of intelligent design approach articles, contrary to popular belief, lack learning ability and intelligent fear tires. As results, offered systems do not take into account real-world traffic conditions such as car and pedestrian counts, as well as delays and waiting times for road users.

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