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Review

State-of-Art Review of Traffic Light Synchronization for Intelligent Vehicles: Current Status, Challenges, and Emerging Trends

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Abstract: The effective control and management of traffic at intersections is a challenging issue in the transportation system. Various traffic signal management systems have been developed to improve the real-time traffic flow at junctions, but none of them have resulted in a smooth and continuous traffic flow for dealing with congestion at road intersections. Notwithstanding, the procedure of synchronizing traffic signals at nearby intersections is complicated due to numerous borders. In traditional systems, the direction of movement of vehicles, the variation in automobile traffic over time, accidents, the passing of emergency vehicles, and pedestrian crossings are not considered. Therefore, synchronizing the signals over the specific route cannot be addressed. This article explores the key role of real-time traffic signal control (TSC) technology in managing congestion at road junctions within smart cities. In addition, this article provides an insightful discussion on several traffic light synchronization research papers to highlight the practicability of networking of traffic signals of an area. It examines the benefits of synchronizing the traffic signals on various busy routes for the smooth flow of traffic at intersections.

Keywords: traffic lights; intersections; synchronization; traffic management and control

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1. Introduction

For ensuring vehicular traffic safety and consistent flow of traffic, traffic signal control and management at road junctions is a challenging problem in the transportation system. Intersections are the points where two or more routes interact with each other. Intersections are where crossroads, pedestrians, vehicles, and bikes change their direction. Intersections act as an obstruction/barrier for smooth traffic flow within the urban areas because of the large number of vehicles traveling from one place to another. This leads to traffic interruption, congestion, and poor control and management of the traffic [1,2]. The intersection delay affects the signal control logic and the travel efficiency of road users [3]. According to a study, over 10% of the traffic delays all over the world are due to the fixed traffic signal delays. It was found that over 295 million traffic hours of delay was observed on major road intersections in the United States [4]. Therefore, precise estimates of time-dependent delays are needed at junctions on metropolitan roadways for traffic control and management.

Intelligent Transportation Systems (ITS) address the complex issue of effective control and management of traffic at junctions. There should be a balance in between safe and effective traffic control at the intersections in order to allow the maximum vehicles to move through while maintaining safety [5]. Nowadays, traffic-light signaling is used to regulate traffic at crucial junctions/crossings by distributing the same green light timings to all routes [6]. The complicated architecture of traffic systems does not coordinate/link the timings of traffic signals with the average daily road traffic, which leads to congestion at the intersections. Various metropolitan cities such as New Delhi, Bangalore, and Mumbai are going through this imbalanced/uneven traffic flow scenario in cities because the majority of working people live in the neighboring areas. The traffic imbalance is generally seen during the peak hours (morning and evening) when people drive from their jobs and residency. Numerous traffic light management systems have been developed to improve the real-time traffic flow at junctions, but none of them have resulted in real-time traffic synchronization or networking. As a result, metropolitan cities require an updated traffic signal control mechanism/technique that updates traffic signal timing and synchronizes the traffic signals at the road intersections on the basis of real-time traffic information.

For large-scale TSC, synchronization provides a number of advantages. Synchronization is not reliant on any network design or set of rules. This is perfect for network traffic management. When the system's most comparable entities synchronize, it is called synchronization. When traffic signal timing and traffic conditions at nearby intersections are comparable or matching, adaptive and smooth traffic signal coordination can be achieved.

This article provides a comprehensive survey of the TSC strategies that have been developed so far. In addition, it provides a detailed analysis of the associated research study and technology advancement status by comparing the existing techniques used for congestion control at road intersections. This article offers an insightful discussion on several traffic light synchronization research papers to highlight the practicability of networking of traffic signals of an area. It emphasizes the gaps in research, open challenges, and provides potential directions for further research in this area.

This paper's key features and contributions are as follows:

- To explore the key role of real-time traffic signal control technology in managing congestion at road junctions within smart cities.
- To summarize the benefits and implementation status of traffic light synchronization and directions for future research for networking traffic lights at intersections of roads.

This article's layout is organized in the following manner. In the beginning, we provide a brief introduction about the history and development background of TSC technology and traffic tight synchronization for intelligent vehicles, and then, the technical benefits of the current traffic light systems are discussed. Then, we compare the existing techniques used for congestion control at road intersections with the help of related work. Afterwards, the synchronization of traffic light development status is summarized and directions for future research for networking traffic lights at road intersections are suggested. Then, typical applications of traffic light networking are discussed. Finally, we conclude the whole paper.

2. Background of Traffic Signal Synchronization for Intelligent Vehicles

The development of traffic signal synchronization for intelligent vehicles is derived from the traffic light control technology. To better understand the synchronization of traffic lights concept, this section outlines the traffic light control technology and analyzes the advantages of synchronization of traffic lights.

2.1. Overview of the Traffic Signal Control Technology

The design of an intelligent traffic light control system is an active research topic. Many researchers are working on the design and development of intelligent traffic signal control systems to solve this stressful issue. Traffic lights can be synchronized as part of regional traffic control methods to enhance the system performance at coordinated junctions. New methods and advanced systems based on artificial intelligence, fuzzy logic, swarm intelligence, evolutionary algorithms [7], image processing, neural network, data fusion, and linear programming etc. have been proposed by the researchers to solve this TSC problem. Table A2 shows the categorization of existing literature on techniques used for congestion control at road intersections. Figure 1 presents the year-by-year trend of the papers published in the area between 1990 and 2021.

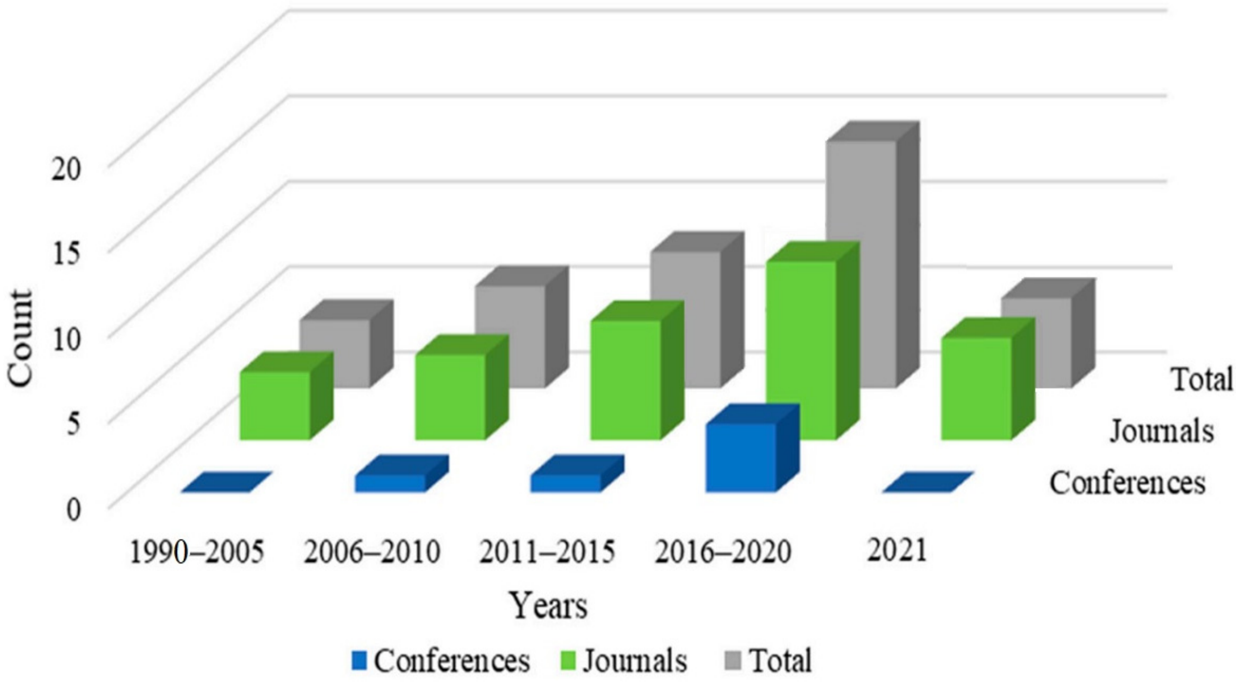

Figure 1. Number of papers published in TSC domain from 1990 to 2021.

Numerous traffic light management algorithms have been developed so far to improve the real-time traffic flow at junctions, but none of them have resulted in real-time traffic synchronization or networking. The rising trend reflects the increasing popularity in the subject and emphasizes the importance of current research. Figure 2 illustrates the taxonomy of the paper.

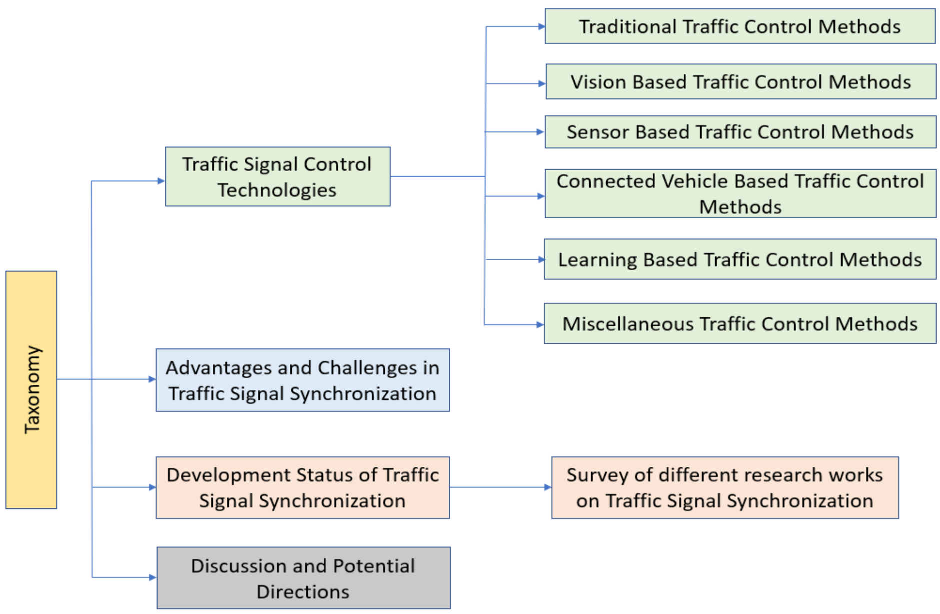

Figure 2. Taxonomy of the article.

2.1.1. Traditional Traffic Control Methods

Many researchers around the world are working in the field of ITS. It has been known for a long time that working on intelligent traffic monitoring and control systems gives various traffic-responsive management solutions that may reduce junction delays dramatically. SCOOT [8], SCATS [9], OPAC [10], RHODES [11], PRODYN [12], and MOTION [13] are examples of adaptive traffic control systems that were designed and implemented in several cities in recent decades. SCOOT [8] and SCATS [9] are adaptive traffic control strategies. These systems use loop/magnetic detectors for gathering traffic data. However, the limitation in these methods is that they do not provide the vehicle's speed, heading, and position. While SCATS is a fully computer (microcomputer, regional computer, and central computer)-based system, it is very expensive to use. Unlike SCOOT and SCATS, PRODYN [12] is not based on cyclic settings. PRODYN addresses the global traffic problem using a two-level iterative computation structure after decomposing the enormous initial optimization problem into multiple smaller problems answered via Dynamic Programming.

These adaptive traffic systems generate a "green signal" for large vehicle flow by optimizing the network's traffic signal offset values according to the current traffic demand. Both real-time and predicted traffic arrivals are used in these systems to optimize the objective functions. These systems have significant drawbacks in terms of cost and functionality because they use cameras and loop/magnetic detectors to track vehicles. The initial implementation cost of the system is around $30,000/junction having a cost of $28,800 per mile/year [14]. Moreover, these systems need a large communication infrastructure that is capable of supporting a centralized control with a high data rate. As a result, many cities across the world have developed systems with high implementation cost.

The Webster procedure was used for fixed signal control at isolated junctions [15] for operation based on measured flows. In this method, the cycle length of every intersection is calculated using Webster's equation. The highest cycle length will act as the cycle length of the whole system. This modified demand-based strategy is viable for real-time undersaturated traffic conditions. In fact, the Traffic Response Urban Control (TUC) technique may be utilized to eliminate the predetermined static signal control sequence, which may lead to more successful outcomes than the original TUC approach. However, the issue is that this technique is quite complex.

2.1.2. Vision-Based Traffic Control Methods

A video camera was utilized to predict and monitor real-time traffic using a dynamic Bayesian networks technique in [16]. In this computationally light method, the distribution of spatial interest and spatiotemporal interest points is classified using the Gaussian mixture model (GMM), and then, the dynamic Bayesian approach is used.

Feature-based approaches [17] and neural networks [18] are also used to recognize and track vehicles coming toward an intersection. Feature-based methods track the features less sensitive to partial occlusion. This approach was ineffective for real-time TSC due to its low accuracy and large storage requirements. In these feature-based methods, binarization, rule-based logic, cameras, and road conditions are used to identify vehicles, which makes the process complex and tedious.

Indu et al. [19] proposed a simple but expensive adaptive traffic signaling system that uses video camera data to provide equal green light timings and then allocates enough time using a fair weight and optimal weight calculation algorithm.

Vehicle tracking and image segmentation algorithms become ineffective for real-time operations because of the computational complexity and longer execution time. However, some are not able to operate effectively at night or in variable weather conditions. Zheng et al. [20] use neural networks to predict the upcoming traffic volume from a 15-min daylight traffic flow on an expressway. As a result of the high complexity and memory needs, this approach is unsuitable for real-time systems.

2.1.3. Sensor-Based Traffic Control Methods

Sharma et al. [21] presented a method that assigns equal green signal duration and arrange fair lane departure at an intersection using the GPS data of the users.

Wang et al. [22] proposed a data fusion approach that collects the data on the speed, position, and direction of the vehicles approaching junctions with the help of GPS sensors in vehicles. This method only improves the traffic flow on a road network; it does not control the traffic signal timing.

Other strategies such as detectors [23], on-board GPS, and big data technologies [24,25] are also used to monitor the arrival and departure of vehicles at a junction to reduce the congestion in urban areas. For monitoring the local traffic in a region, sensors and traffic servers are also used. Embedded technology [26] records the GPS data of vehicles and sends it to the traffic monitoring system through GSM/GPRS. This method has a very high implementation cost.

Coll et al. [27] introduced an adaptive system based on linear programming that controls the traffic lights and reduces the waiting time at intersections. This method uses the data gathered from the real-time sensors placed at every intersection.

TSC systems based on Wireless Sensor Network (WSN) have also been used at isolated intersections in [28,29]. Rida et al. [28] proposed a time-fragment based control mechanism that splits the time and calculates the percentage of green ratio. Yousef et al. [30] proposed a connected vehicle-based algorithm for isolated junctions that uses vehicle proximity for releasing vehicle platoons.

2.1.4. Connected Vehicle-Based Traffic Control Methods

Another technique to adaptive decision making is the Virtual Traffic Light (VTL) approach [31], which is a Vehicle-to-Vehicle (V2V) traffic control system with enormous potential, since it may increase traffic flow by more than 30% while eliminating the usage of expensive traffic signals. VTL makes use of V2V communication using the Signal Phase and Timing (SPaT) message and Basic Safety Message (BSM) from the Dedicated Short Range Communication (DSRC) radio for traffic management at intersections. The drawback of this approach is that it requires full penetration of DSRC technology in vehicles, which is not possible at the present time. Furthermore, V2V communications in VTL could come across non-LoS conditions, which makes rapid decision making extremely challenging [32].

A connected vehicle (CV) initiative [33,34] was established by the Virginia Department of Transportation (VDOT) to focus on different V2V and Vehicle-to-Infrastructure (V2I) applications. This program intends to lower the cost of infrastructure for roadside guidance signs and traffic lights by using DSRC technology. However, the complete penetration of the DSRC is required for the connected corridor setup.

Tonguz et al. [35] presented a DSRC-based traffic management method for road intersections. Roads with DSRC-equipped automobiles are given precedence under this system. Even if a small number of vehicles have DSRC technology, this strategy can be effective in reducing the average waiting time on each traffic light. When compared to alternative TSC systems that use detectors, sensors, and cameras, this technique provides a cost-effective solution for traffic management in urban areas by simply using DSRC Road-Side Units (RSUs).

Dresner et al. [36] describes autonomous intersection management (AIM) utilizing multiagent systems, in which drivers and junctions are considered as autonomous entities. Intersections employ a completely new reservation-based technique based on a detailed communication protocol in this mechanism.

2.1.5. Learning-Based Traffic Control Methods

Many studies have recommended using reinforcement learning (RL) to regulate traffic lights and reduce traffic congestion [37,38]. Unlike traditional TSC systems, which depend mainly on predefined models, RL may learn immediately from input as shown in Figure 3. Every junction in RL is portrayed as an agent that optimizes its input-based travel time from the surroundings when the action (i.e., the traffic lights) is set [39].

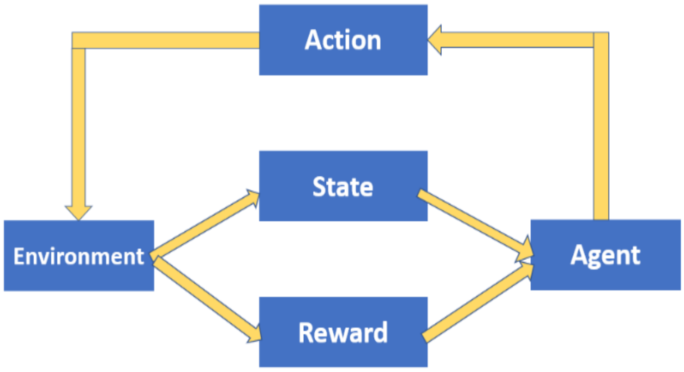

Figure 3. Reinforcement learning working procedure.

Zheng et al. [40] suggested a FRAP model based on phase competitive modeling, which achieves invariance in traffic flow flipping and rotation conditions. In complicated traffic situations and multi-junction configurations, this system discovers better solutions and delivers greater performance than prior learning methods.

To overcome the fixed traffic signal problem, ref. [41] proposes a novel MARL (Multi-agent Reinforcement Learning) approach called Co-DQL, which stands for co-operative double Q-learning. The overestimation problem that affects traditional independent Q-learning is avoided with Co-DQL. TSC simulators are used to test various traffic flow conditions. MARL provides a new reward allocation mechanism for boosting agent stability and resilience.

Joo et al. [42], WeiHua et al. [43], and Zhang et al. [44] investigated some recent improvements in RL techniques that may be applied to solve difficulties with traffic signal regulation. They describe the usage of PPO, A2C, and ACKTR algorithms to handle the problem of partial vehicle detection.

For TSC, Zhang et al. [45] proposes a deep Q-learning approach with partial vehicle identification using DSRC. This system has the benefit of being able to identify cars utilizing different detection technologies such as LTE/5G, BLE 5.0, and RFID.

2.1.6. Miscellaneous Traffic Control Methods

Dezani et al. [46,47] used genetic algorithm (GA) to optimize traffic signals in real time and determine the optimal paths for cars. With the use of a basic neighborhood algorithm, Sabar et al. [48] enhanced GA by using a local search strategy that lowers the average delay in traffic even more than feasible.

In a nine-junction network, Li and Sun [49] suggested a multifunctional GA for traffic optimization. However, this method did not use real-time traffic data.

For traffic light scheduling, refs. [50–52] employ a particle swarm optimization (PSO) technique to regulate traffic lights to minimize the waiting time at intersections so that vehicles can reach their destination in the minimum feasible time. Other swarm intelligence algorithms used for TSC include Ant Colony Optimization [53,54] and Harmony search [55,56].

Milanés et al. [57] presented a V2V communication-based method for reducing traffic congestion at intersections by utilizing the speed and location of autonomous vehicles.

Bi et al. [58,59] presented a type-2 FLC system to solve the coordination and complicated uncertainty issues in heavy but organized traffic. (based on fuzzy and Q learning). Firdous et al. [60,61] developed a real-time control system based on fuzzy logic to reduce vehicle waiting times at intersections.

3. Advantages of Synchronizing the Traffic Lights

The primary goals of TSC technology is to improve traffic safety and travel quality as well as lower the pollution caused by vehicles. However, due to the rapid growth of numerous issues such as the increase in the number of vehicles on the road, traffic jams, and increased pollution over the last 20 years, even emerging countries have relied on the most basic traffic signal control technologies.

Traffic congestion has been a serious concern in metropolitan areas as vehicular traffic has increased. The problem is even worse at road intersections, where pre-timed traffic signals produce delays, increased vehicle activity costs, and air pollution. Time delays are least caused in roadways and rural areas; they are frequently observed in metropolitan cities. Consequently, metropolitan traffic shapes the concerned area of research on delays caused for vehicles and pedestrians. The basic objective of signalized junctions is to decrease the problems that are experienced more at unsignalized crossing points and rotaries and furthermore to give an equivalent chance to all vehicles to cross the intersection.

To address these concerns, traffic light synchronization is a technique in which a vehicle traveling along one side of the road at a specific speed can continue to the opposite end of the road indefinitely by obtaining the maximum number of green lights at the intersections.

4. Development Status of Synchronization of Traffic Lights

The synchronization of traffic signals across a city is supported by traffic light control frameworks. When automobiles pass through a junction network, these frameworks lower the amount of time they have to wait. Despite the previous research in this domain over the last five decades, improved traffic signal control framework administration is still required.

To enhance traffic flow efficiency at high-density junctions, Hu et al. [62] employed a long green and long red (LGLR) technique for synchronizing the traffic lights of an area. For smoothening the traffic flow across the city, ref. [63] employed a real-time system for the synchronization of traffic lights using multiagent fuzzy logic and the Q-learning approach.

Amogh et al. [64] presented a method for improving traffic synchronization efficiency by dynamically modifying timing settings. This system uses traffic cameras to obtain vehicle density at each intersection and then uses OpenCV to conduct operations on the pictures.

Khan et al. [65] proposes a self-organized TSC system based on sensors. It improves the efficiency of traffic flow and reduces the waiting time at intersections. In comparison to traditional traffic management systems, this technology gives more information and prioritizes the road with a large number of cars at an intersection first. However, this approach does not synchronize the traffic lights of all the intersections.

V2I connectivity was utilized in [66] for the networking of junctions and other road signs. It is used to transmit information on infrastructure such as speed restrictions, road alterations, and traffic light information to smart cars.

Sirikham et al. [67] presented a traffic light synchronization system that used two control boards, a sender and receiver. These control boards use the NodeMCU V.2 (2.4 GHz WiFi) to synchronize the control signals by ESP-NOW protocol, as shown in Figure 4. However, this system works only for single-lane traffic control.

Kumar et al. [68] proposed a synchronization method for two traffic signals using the Long Range (LoRa) module. It uses the time division algorithm to get the traffic information so that the rerouting of vehicles can be done during the peak hours. This concept helps the vehicles reach their destination in the shortest possible time by taking the fastest route.

A synchronization scheme for traffic light controllers based on an explicit finite state model (FSM) is presented in [69]. FSM is modeled using Verilog HDL, and the coding is done using Xilinx Spartan-6 XC6LX16-CS324 FPGA. The machine is merely simulated with six states, which are selected using the traffic control method. Each state provides the appropriate delay, and the requisite traffic signals are turned ON/OFF for that delay. For example, just two routes are picked, and a control algorithm controls the traffic lights on those roads. This study introduced a flexible architecture that uses a clock divider to give a delay in a certain state and discusses the difficulty of modeling the FSM. The topic of selecting a state-encoding technique was also discussed.

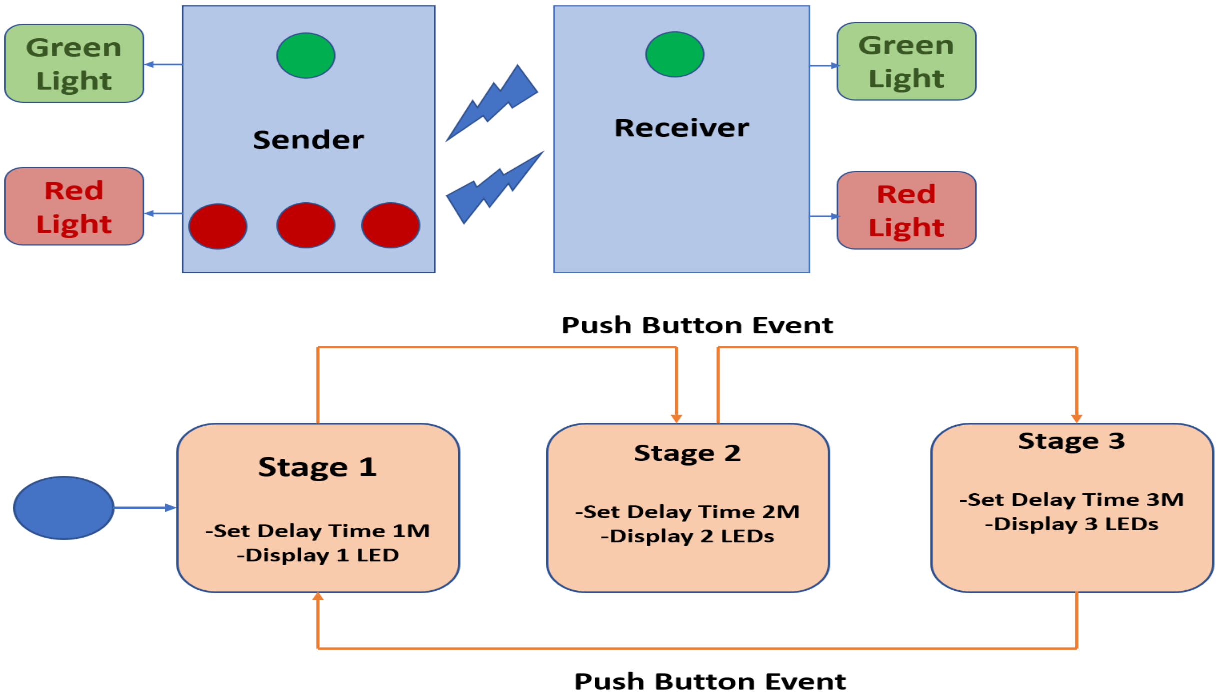

Figure 4. Overview of Single-lane traffic control using NodeMCU V.2 [67].

A self-synchronization mechanism for aerial vehicles and air traffic control (ATC) systems was introduced in [70] for avoiding collision. It assists in obtaining a unique path for each aircraft in order to reduce conflict, but if this is not possible, the system gives an optimum option to utilize other shared resources.

An adaptive, flexible, and robust distributed TSC method based on spontaneous synchronization was introduced in [71], which occurs when local interaction leads to a stable state. In this method, every junction is represented by a phase-oscillator model. The global coordination is achieved by synchronizing these phase oscillators to maintain the platoons flow.

Adacher et al. [72,73] proposed a distributed algorithm for solving the synchronization problem of urban traffic signals. They calculated the weighted sum of delays at signalized intersections by CTM-UT; i.e., (Cell Transmission Model for Urban Traffic) via simulation. A surrogate method (SM) based on an online and stochastic control scheme has been used to synchronize the traffic signals.

An IoT-based traffic signal synchronization method was proposed in [74] to reduce the traffic congestion at road intersections. This method allows the vehicles to travel a long distance by minimizing the number of STOP and GO occurrences by adapting the traffic light phases at the road intersections (Figure 5). This method reduces the average travel time up to 39% using traffic simulator SUMO in comparison to the other fixed time and non-synchronized traffic control strategies.

Nesmachnow et al. [75] introduced the synchronization of traffic lights using a parallel evolutionary algorithm for Bus Rapid Transit systems by considering various features such as real maps and mobility data and analyzing these features for optimization. This method improves the average speed of public transport up to 15.3% and other vehicles up to 24.8%. Using this method, different priorities can be assigned to buses and other vehicles using a multi-objective optimization analysis.

A model for synchronizing the traffic lights at road intersections is presented in [76]. This method uses a hybrid metaheuristic approach that combines variable neighborhood search and Tabu search into one algorithm. The method incorporates a memory structure into an iterative local search, allowing for a wider range of solutions. Certain changes such as modification of a mixed integer linear model's constraints and the generalization of some bounds for integer variables were made to the MAXBAND in this algorithm.

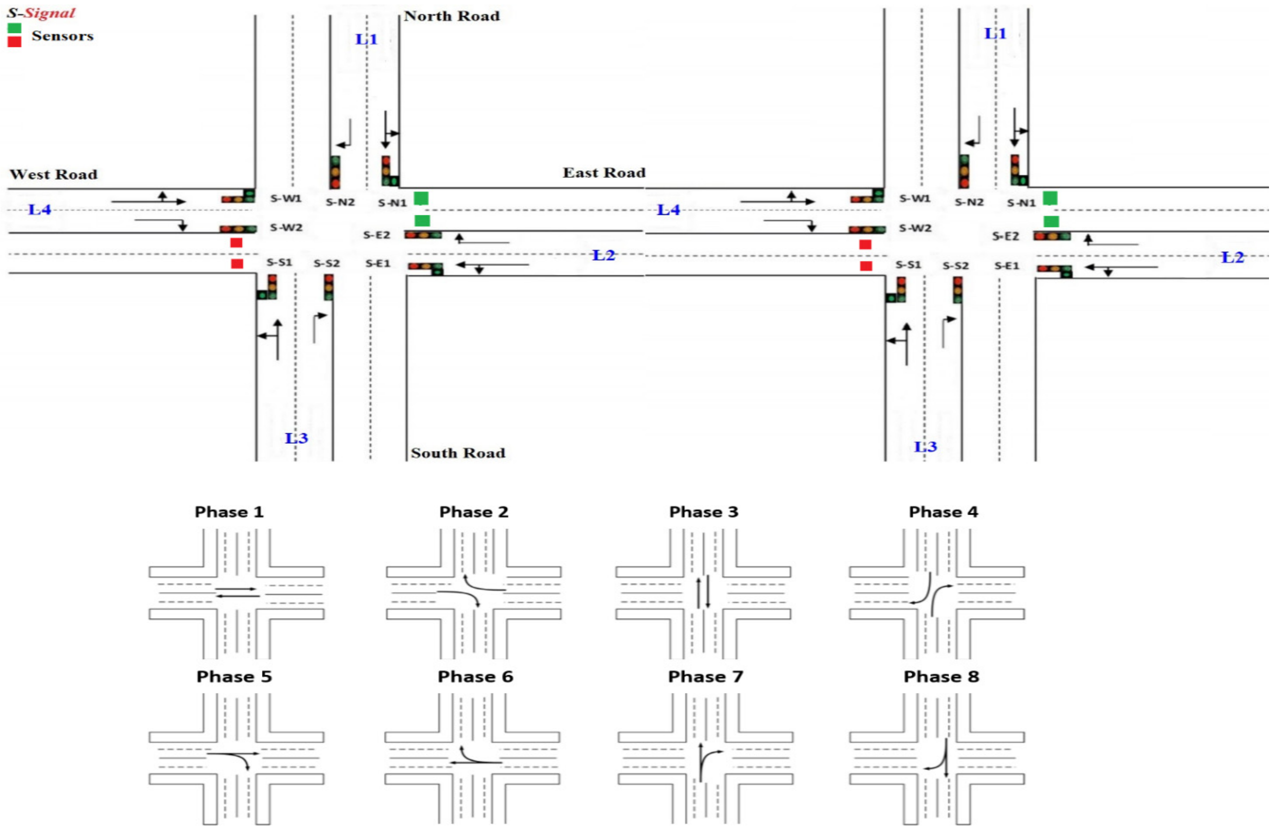

Figure 5. IoT-based mechanism for traffic signal synchronization using sensor deployment on adjacent junctions [74].

In [77], the decentralized spatial decomposition of a network has been used for the synchronization of traffic signals at the road junctions. This method uses the platoon model to calculate the weighted sum of delays induced by signalized crossings. To get a spatial breakdown of the network, distributed consensus approaches were utilized. Using the distributed communication architecture, each semaphore distributes information with its neighbors in a totally dispersed manner, hence removing the need for a central authority. A surrogate technique is used for synchronizing the traffic signals given the subnetwork.

A self-synchronization paradigm for connected vehicles in traffic networks has been used in [78] to solve the coordination problem at junctions. For safe spacing between cars moving on the same route, coordinating safe crossing at junctions with competing flows, a multilayer decentralized control method is utilized. The Kuramoto equation is used to synchronize the phase and frequency of the network's agents (vehicles). This approach considered the vehicles as oscillating agents instead of the traffic lights. This technique is classified as a decentralized approach since it is interconnected to achieve network-wide synchronization. It combines the advantages of coordinating vehicle crossings at particular crossroads with synchronizing flow from nearby junctions in this way.

In [79], floating car data (FCD) was used to synchronize the traffic signals at intersections. This approach used the penetration rate of "instrumented" vehicles to obtain synchronization in adaptive traffic light systems based on floating car data (FCDATS) in competition cooperation. This technology increases the traffic safety and energy efficiency of transportation systems.

Yang et al. [80] used cellular automaton for synchronizing traffic signals by building a network model of two intersections. By changing the signal duration and green time offset, the synchronization of the signals is investigated, and results are obtained in MATLAB. An optimal signal scheme reduces the overall delay and increases the traffic flow at road junctions. Next, the network's essential features, such as fundamental and time–space diagrams, are addressed.

Li et al. [81] introduced a time synchronization method among VANET devices, claiming that On-Board Units (OBUs) can synchronize with other OBUs or RSUs on their own initiative. This technique lowers the synchronization error to less than 0.3 ms when there is no center node in the Basic Service Set, which fulfills the accuracy criterion of the VANET specification. In the Basic Safety System (BSS), a time-synchronization mechanism is introduced in which there is no central node, resulting in a more stable network. This method can achieve nanosecond precision while avoiding estimate errors. This method can correctly implement time synchronization in a BSS. In addition, there is a topology for the whole VANET in order to achieve time synchronization among RSUs. As a result, the amount of handoff done by OBUs can be drastically decreased. It can also greatly increase the system's stability.

A survey of the synchronization techniques is presented in [82], which addressed various situations and current cellular network generations while reviewing synchronization standards and approaches for V2V and Device-to-Device (D2D) enabled cellular networks. They looked at the major channels, entities, and signals that V2V and D2D enabled cellular networks employ for synchronization in various circumstances. Furthermore, to highlight current developments and give future perspectives, the focus is on the synchronization in V2V and Vehicle to Everything (V2X).

Du et al. [83] presented a rule-based algorithm for V2X speed synchronization at road junctions. Vehicles entering from separate lanes form a virtual platoon. When traffic is light, this system allows for fewer unnecessary stops, resulting in energy savings and an increase in average speed. As a result, speed synchronization is no longer effective, as the volume of traffic increases and cars must come to a halt. Virtual platooning is expanded here by introducing some principles that enable a virtual platoon to dynamically modify its whole behavior in response to traffic flow growth while maintaining safety. This technique is extremely efficient in boosting average speed while maintaining the intersection's high capacity.

The significance of nearby junctions has not been studied in the above cited research works. The categorization of existing literature on synchronization of traffic signals is shown in Table A1 (Appendix A). These works are restricted to one intersection only, which makes the problem appearance more complex and extensive in scope. More efforts should be made in order to obtain maximal modeling, control, and monitoring of several synchronized junctions.

5. Discussion and Potential Directions

The primary goals of TSC technology research were to improve traffic safety, improve trip quality, and minimize pollution emissions. Traffic congestion has been a serious concern in metropolitan areas as vehicular traffic has increased. The problem is even worse at road intersections, where pre-timed traffic signals produce delays, increased vehicle activity costs, and air pollution. Delay is caused by the status of one light at a crossroad, which impacts the flow of traffic at neighboring intersections also. Additionally, the traditional traffic system does not account for mishaps, road closures, or vehicle breakdowns, which contribute to travel delays. Furthermore, a major issue is the seamless movement of emergency vehicles with greater demands, such as emergency vehicles, ambulances, fire brigade, police, and VIPs, through crossing points. As a result, the regular traffic system must be upgraded in order to alleviate traffic congestion and minimize waiting times and travel time as well as maximize vehicle safety, efficiency, and economic benefits [84].

The majority of traffic monitoring technologies at junctions rely on high-cost cameras and sensors that are difficult to install and maintain. Computationally intensive traffic signal control technologies are utilized at road junctions. As a result, real-time signal control tactics at road crossings must be enhanced in order to eliminate traffic congestion. A massive disadvantage is that the traditional methods do not synchronize the traffic signals of a region.

To address these concerns, traffic light synchronization is a technique in which a vehicle traveling along one side of the road at a specific speed can continue to the opposite end of the road indefinitely by obtaining the maximum number of green lights at all the intersections. Traffic signal synchronization is required so that the green light cycles for a series of junctions can be synchronized, enabling the greatest number of automobiles to pass through while avoiding waits and delays.

Synchronization can be done at different levels. Figure 6 shows traffic signal synchronization at level I and level II. We can define the levels of synchronization within an area. One will be the inner circle and another will be the outer circle, where the inner circle reflects peer junctions of level I and the outer circle reflects the peer junctions of level II. Level I consists of the nearest neighboring junctions, and level II consists of the junctions falling in the external area. The intelligence at level II also takes into consideration the density of the adjacent junctions. These levels of synchronization will help in reducing the congestion at neighboring intersections. In this way, the system will become smart when it is connected to the server.

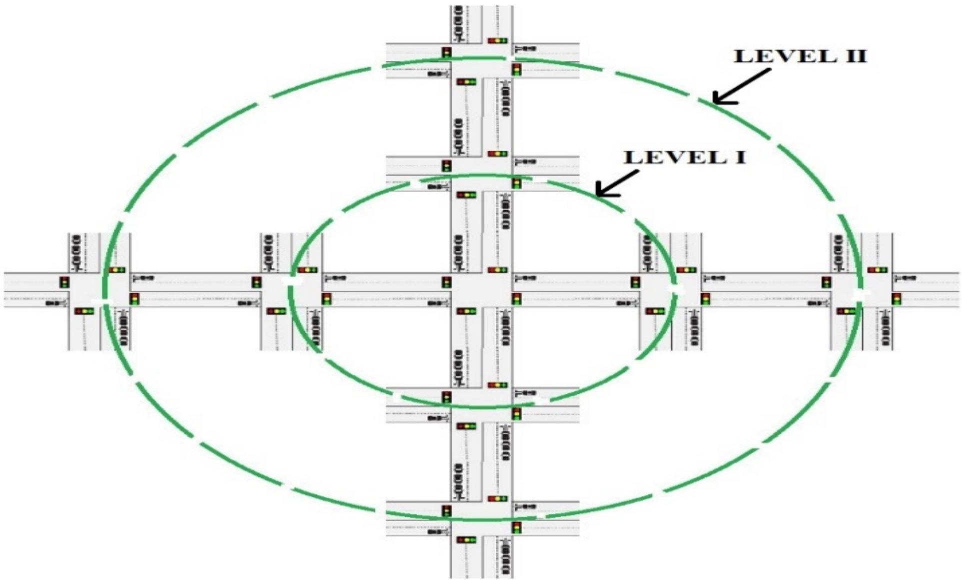

Figure 6. Levels of synchronization.

The designed traffic signal synchronization framework can work efficiently with any technology, whether it is DSRC, image processing, sensors, or any other technology that is used to collect traffic density at intersection. With minor changes to the current system, new junctions can also be incorporated for synchronization. In this way, it is possible to extend this system for covering all the intersections of a city or state, thus moving toward a well-coordinated and lucid method of traffic control.

6. Conclusions

Traffic signal synchronization for intelligent vehicles is a revolutionary innovative technology with exceptional potential in the intelligent transportation systems. Hence, this article provides a comprehensive survey on traffic light synchronization techniques for intelligent vehicles. First of all, we outline the different traffic light control technologies used for congestion control at intersections. Then, typical applications of synchronization of traffic signals are discussed. Next, we summarize the development status of synchronization of traffic signals for intelligent vehicles by surveying all the research works on traffic signal synchronization. In addition, we discuss many emerging and potential directions of traffic light networking. This study will provide researchers with the basis for more understanding and investigation of the synchronization of traffic lights for intelligent vehicles.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

Appendix A

Table A1. Categorization of existing literature on synchronization of traffic signals.

Reference Number	Objective	Strategies Used	Disadvantages	Comments
[62]	Traffic light synchronization strategy for saturated road networks	Long green and long red method for highly saturated road networks	Not suitable to the undersaturated HGRN	• Control the arrival and departure of queues • Increase the efficiency of traffic flows to the maximum level at signalized junctions
[63]	To synchronize traffic signals	Multiagent fuzzy logic and Q-learning		• Fully distributed multiagent architecture with no central supervising or synchronizing agent • Coordination between agents through communication of decision data
[64]	Traffic signal synchronization with dynamic timer value	Image processing and Raspberry Pi in synchronization with cloud	• Camera implementation cost is very high • System implemented on a small scale (in the laboratory, not in real-life scenarios) • Conflicts can arise when two emergency vehicles arrive on opposite sides of a junction at the same time	• Obtains the vehicle density using traffic cameras on every side of the junction using image processing on OpenCV • Provides priority to emergency vehicles • Increased efficiency in with dynamic change in timer value
[65]	Self-organized traffic light control based on sensors	• Pressure sensors to detect vehicles approaching the intersection • Microcontroller and Zigbee module to transfer the information to signal controller	No synchronization of traffic signals	Increases traffic flow efficiency and reduce the waiting time at intersections

Table A1. *Cont.*

Reference Number	Objective	Strategies Used	Disadvantages	Comments
[67]	Wireless traffic light synchronization system	• Uses two control boards (sender and receiver) • Control boards use NodeMCU V.2 (2.4GHz WiFi) for synchronization of control signals by ESP-NOW protocol	For single-lane traffic control only	• Uses wireless communication • Increased safety
[68]	Rerouting and synchronization of traffic	Using the Long Range (LoRa) module	Synchronization for two traffic signals only	• Congestion control at intersection by rerouting vehicles • Vehicles reach their destination in the shortest possible time by taking the fastest route
[69]	Synchronization scheme for traffic light controller	• Based on explicit finite state model (FSM) • FSM modeled using Verilog HDL and coding is done using Xilinx Spartan-6 XC6LX16- CS324 FPGA	Difficulty of modeling the FSM	Flexible architecture that uses a clock divider to give a delay in a certain state
[71]	Distributed traffic signal control method based on spontaneous synchronization	• Every junction is represented by a phase-oscillator model • These oscillators are synchronized to get the desired global coordination	Mathematical complexity	• Local interaction leads to a stable state • Maintain the platoons flow
[72,73]	Distributed approach for synchronizing traffic signals	CTM-UT i.e., (Cell Transmission Model for Urban Traffic) via simulation	Computational complexity	Surrogate method (SM), based on an online and stochastic control scheme, used for synchronizing the traffic signals
[74]	IoT-based traffic signal synchronization method	Uses magnetic sensors as the main IoT sensing technology	Not suitable for all kinds of road networks	Reduces the average travel time up to 39% using the road traffic simulator SUMO
[75]	Traffic signals synchronization for Bus Rapid Transit systems	Parallel evolutionary algorithm	In the context of Bus Rapid Transit systems	• Improves the average speed of public transport up to 15.3% and other vehicles up to 24.8% • Different priorities can be assigned to buses and other vehicles using a multi-objective optimization analysis
[76]	Model for synchronizing the traffic lights at road intersections	Hybrid metaheuristic approach that combines variable neighborhood search and Tabu search	Mathematical and computational complexity	Flexible and robust approach

Table A1. *Cont.*

Reference Number	Objective	Strategies Used	Disadvantages	Comments
[77]	Decentralized spatial decomposition of network for synchronization of traffic signals at the road junctions	Uses platoon model to calculate the weighted sum of delays induced by signalized crossings	More robust to failure	Distributed communication architecture for networking of traffic lights
[79]	To synchronize the traffic signals at intersections	Using floating car data (FCD)	Only a beginning step toward addressing the synchronization problem; need for more comprehensive optimization algorithms for general cases	Increases the traffic safety and energy efficiency of transportation systems
[80]	Traffic signal synchronization in a small urban road network	Cellular automation	Synchronization for two traffic signals only	Minimize total delay and maximize the flow
[82]	Survey of the synchronization techniques	Highlight current developments and give future perspectives on synchronization in V2V and V2X	Not Specified	Reviews synchronization standards and approaches for V2V and D2D-enabled cellular networks
[83]	Vehicle-to-Everything (V2X) speed synchronization at road junctions	Rule-based algorithm	Based on optimal scheduling	Improves the performance of cooperative intersection management

Table A2. Categorization of existing literature on techniques used for congestion control at road intersections.

Reference Number	Objective/Context	Intersection			Traffic Signal Control Strategies		Source of Data Collection			Comments
		Isolated	Single	Network	Real Time	Fixed Time	Sensors/Detectors	Field Cameras	GPS/DSRC	
[8]	Split Cycle Offset Optimization Technique (SCOOT)			✓	✓		Detectors			• Minimize stops and delays at intersections by synchronizing adjacent signals • Disadvantage: Increased overhead during heavy traffic in large complicated network
[9]	Sydney Cooperation Adaptive Traffic System (SCATS)			✓	✓		Sensors			• Monitors real-time traffic signals and a volume of traffic • Reduces average waiting time, travel time, and fuel consumption

Table A2. *Cont.*

Reference Number	Objective/Context	Intersection			Traffic Signal Control Strategies		Source of Data Collection			Comments
		Isolated	Single	Network	Real Time	Fixed Time	Sensors/Detectors	Field Cameras	GPS/DSRC	
[10]	Optimized Policies for Adaptive Control (OPAC)			✓	✓		✓			• Calculates signal timing by minimizing total delay and stops performance function • No special features for priority/pre-emption on the system level • No explicit features for pedestrians or oversaturation conditions
[11]	Real-Time Hierarchical Optimized Distributed Effective System (RHODES)			✓	✓		✓			Decomposition of traffic network by modules that individually deal with sub-problems
[15]	Traffic signal control of road networks in real time	✓				✓				Based on Webster procedure
[16]	Traffic monitoring and prediction on roads		✓		✓			✓		• Uses dynamic Bayesian networks approach • Real-time prediction and classification of the state of a road • Improvement of travel and transit information
[17,18]	Travel time prediction framework	Freeway			✓		Robust Travel Time framework			• Based on state-space neural network • Based on Bayesian combined neural network
[19]	To reduce waiting time of vehicles at road intersections		✓		✓			✓		A video-based adaptive traffic signaling system
[21]	Assign equal green signal durations and arrange fair lane departure at an intersection			✓	✓				GPS	Adaptive traffic signal timings and lane scheduling
[22]	To enhance the flow of traffic on current road network using a data fusion approach			✓	✓				GPS	• Using floating car data (FCD) • Improve traffic flows on roads
[23]	Traffic signal control system		✓		✓		✓			• Using two-stage fuzzy control system • Reduces the average vehicle delay
[27]	To minimize the waiting time at a crossroad			✓	✓		✓			• Using a linear programming model • Minimize the queue length of vehicles waiting at intersections

Table A2. *Cont.*

Reference Number	Objective/Context	Intersection			Traffic Signal Control Strategies		Source of Data Collection			Comments
		Isolated	Single	Network	Real Time	Fixed Time	Sensors/Detectors	Field Cameras	GPS/DSRC	
[28,29]	WSN-based traffic light control systems			✓	✓		✓			• Low-cost installation to existing traffic road infrastructure • Self-configurable, easy installation of new traffic sensor nodes
[30]	TSC at signalized intersections	✓			✓		V2V communication			• Using connected vehicle technology • Minimize average delay
[31]	V2V traffic control for traffic management at intersections		✓		✓				DSRC	Virtual Traffic Light phenomenon based on DSRC
[33,34]	Removal of intersection traffic signal infrastructures			✓	✓				DSRC	• Connected and autonomous vehicle program (CV) • V2V and V2I applications
[35]	Intersection traffic control scheme				✓				DSRC	Based on DSRC-Actuated Traffic Control
[36]	Autonomous intersection management (AIM)			✓	✓		Simulator			• Operate both human-driven and autonomous cars • Prioritizes emergency vehicles
[40]	Reinforcement Learning based traffic signal control			✓	✓		Mathematical Model			• FRAP (Flipping and Rotation and considers All Phase configurations) model • Gives priority to the road with high traffic density • Better performance in complicated traffic situations and multi-junction environment
[41]	Traffic signal control at a very large scale using Multiagent reinforcement learning (MARL) technique			✓	✓		Simulator			• Using cooperative double Q-learning (Co-DQL) • Stable and robust
[45]	Deep Q-learning algorithm based system for partially detected intelligent vehicles			✓	✓				DSRC	• Minimize the vehicles waiting time at junctions (even if the detection rate of vehicles in low) • Can be used with different detection technologies such as LTE/5G, BLE 5.0, and RFID

References

1. Nielsen, O.A.; Frederiksen, R.; Simonsen, N. Using Expert System Rules to Establish Data for Intersections and Turns in Road Networks. *Int. Trans. Oper. Res.* **1998**, *5*, 569–581. [CrossRef]
2. Sigua, R.G. *Fundamentals of Traffic Engineering*; University of the Philippines in Diliman: Quezon City, Philippines, 2008; p. 327. Available online: https://www.crcpress.com/Fundamentals-of-Picoscience/Sattler/p/book/9781466505094#googlePreviewContainer (accessed on 20 September 2021).
3. Heidemann, D. Queue length and delay distributions at traffic signals. *Transp. Res. Part B Methodol.* **1994**, *28*, 377–389. [CrossRef]
4. The National Traffic Signal Report Card. Available online: https://www.researchgate.net/publication/295961075_The_national_traffic_signal_report_card (accessed on 20 September 2021).
5. Chen, L.; Englund, C. Cooperative Intersection Management: A Survey. *IEEE Trans. Intell. Transp. Syst.* **2015**, *17*, 570–586. [CrossRef]
6. Zaghal, R.; Thabatah, K.; Salah, S. Towards a smart intersection using traffic load balancing algorithm. In Proceedings of the 2017 Computing Conference, London, UK, 18–20 July 2017.
7. Shaikh, P.W.; El-Abd, M.; Khanafer, M.; Gao, K. A Review on Swarm Intelligence and Evolutionary Algorithms for Solving the Traffic Signal Control Problem. *IEEE Trans. Intell. Transp. Syst.* **2020**, *23*, 48–63. [CrossRef]
8. Bing, B.; Carter, A.T. SCOOT: The World's Foremost Adaptive Traffic Control System. Traffic Technology International'95. 1995. Available online: https://trid.trb.org/view/415757 (accessed on 20 September 2021).
9. Sims, A.; Dobinson, K. The Sydney coordinated adaptive traffic (SCAT) system philosophy and benefits. *IEEE Trans. Veh. Technol.* **1980**, *29*, 130–137. [CrossRef]
10. Gartner, N.H. Demand-responsive traffic signal control research. *Transp. Res. Part A Gen.* **1985**, *19*, 369–373. [CrossRef]
11. Mirchandani, P.; Head, K.L. A real-time traffic signal control system: Architecture, algorithms, and analysis. *Transp. Res. Part C Emerg. Technol.* **2001**, *9*, 415–432. [CrossRef]
12. Henry, J.; Farges, J.; Tuffal, J. The Prodyn Real Time Traffic Algorithm. In Proceedings of the Control in Transportation Systems, Baden-Baden, Germany, 20–22 April 1983; Elsevier BV: Amsterdam, The Netherlands, 1984; pp. 305–310.
13. Brilon, W.; Wietholt, T. Experiences with Adaptive Signal Control in Germany. *Transp. Res. Rec. J. Transp. Res. Board* **2013**, *2366*, 9–16. [CrossRef]
14. Costs | U.S. Department of Transportation. Available online: https://www.itskrs.its.dot.gov/costs (accessed on 20 September 2021).
15. Kouvelas, A.; Aboudolas, K.; Papageorgiou, M.; Kosmatopoulos, E.B. A Hybrid Strategy for Real-Time Traffic Signal Control of Urban Road Networks. *IEEE Trans. Intell. Transp. Syst.* **2011**, *12*, 884–894. [CrossRef]
16. Chaudhary, S.; Indu, S.; Chaudhury, S. Video-based road traffic monitoring and prediction using dynamic Bayesian networks. *IET Intell. Transp. Syst.* **2018**, *12*, 169–176. [CrossRef]
17. Hadi, R.A.; Sulong, G.; George, L.E. Vehicle Detection and Tracking Techniques: A Concise Review. *Signal Image Process. Int. J.* **2014**, *5*, 1–12. [CrossRef]
18. van Lint, J.; Hoogendoorn, S.; van Zuylen, H. Accurate freeway travel time prediction with state-space neural networks under missing data. *Transp. Res. Part C Emerg. Technol.* **2005**, *13*, 347–369. [CrossRef]
19. Indu, S.; Nair, V.; Jain, S.; Chaudhury, S. Video based adaptive road traffic signaling. In Proceedings of the Seventh International Conference on Distributed Smart Cameras (ICDSC), Palm Springs, CA, USA, 29 October–1 November 2013.
20. Zheng, W.; Lee, D.-H.; Shi, Q. Short-Term Freeway Traffic Flow Prediction: Bayesian Combined Neural Network Approach. *J. Transp. Eng.* **2006**, *132*, 114–121. [CrossRef]
21. Sharma, K.K.; Indu, S. GPS Based Adaptive Traffic Light Timings and Lane Scheduling. In Proceedings of the 2019 IEEE Intelligent Transportation Systems Conference (ITSC), Auckland, New Zealand, 27–30 October 2019; pp. 4267–4274.
22. Tiedong, W.; Jingjing, H. Applying floating car data in traffic monitoring. In Proceedings of the 2014 IEEE International Conference on Control Science and Systems Engineering, Yantai, China, 29–30 December 2014; pp. 96–99.
23. Lin, Y. The Design and Simulation of Intelligent Traffic Signal Control System Based on Fuzzy Logic. In *Foundations of Intelligent Systems*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 965–973. [CrossRef]
24. Tanwar, R.; Majumdar, R.; Sidhu, G.S.; Srivastava, A. Removing traffic congestion at traffic lights using GPS technology. In Proceedings of the 2016 6th International Conference—Cloud System and Big Data Engineering (Confluence), Noida, India, 14–15 January 2016; pp. 575–579.
25. Liu, Y. Big Data Technology and Its Analysis of Application in Urban Intelligent Transportation System. In Proceedings of the 2018 International Conference on Intelligent Transportation, Big Data & Smart City (ICITBS), Xiamen, China, 25–26 January 2018; pp. 17–19.
26. Liping, X.; Dangying, L. A Novel Embedded Vehicle Terminal for Intelligent Transportation. In Proceedings of the 2014 Fifth International Conference on Intelligent Systems Design and Engineering Applications, Hunan, China, 15–16 June 2014; pp. 52–54. [CrossRef]
27. Coll, P.; Factorovich, P.; Loiseau, I.; Gómez, R. A linear programming approach for adaptive synchronization of traffic signals. *Int. Trans. Oper. Res.* **2013**, *20*, 667–679. [CrossRef]
28. Rida, N.; Hasbi, A. Traffic Lights Control using Wireless Sensors Networks. In Proceedings of the 3rd International Conference on Smart City Applications, Tetouan, Morocco, 10–11 October 2018. [CrossRef]

29. Yousef, K.M.; Al-Karaki, J.N.; Shatnawi, A.M. Intelligent Traffic Light Flow Control System Using Wireless Sensors Networks. *J. Inf. Sci. Eng.* **2010**, *26*, 753–768.
30. Liang, X.; Guler, S.I.; Gayah, V.V. An equitable traffic signal control scheme at isolated signalized intersections using Connected Vehicle technology. *Transp. Res. Part C Emerg. Technol.* **2019**, *110*, 81–97. [CrossRef]
31. Zhang, R.; Schmutz, F.; Gerard, K.; Pomini, A.; Basseto, L.; Hassen, S.B.; Ishikawa, A.; Ozgunes, I.; Tonguz, O. Virtual Traffic Lights: System Design and Implementation. In Proceedings of the 2018 IEEE 88th Vehicular Technology Conference (VTC-Fall), Chicago, IL, USA, 27–30 August 2018; pp. 1–5. [CrossRef]
32. Tonguz, O.K. Red light, green light—No light: Tomorrow's communicative cars could take turns at intersections. *IEEE Spectr.* **2018**, *55*, 24–29. [CrossRef]
33. VDOT Launches Smarter Roads. Available online: https://augustafreepress.com/vdot-launches-smarterroads/ (accessed on 20 September 2021).
34. Virginia Connected Corridors | Virginia Tech Transportation Institute. Available online: https://www.vtti.vt.edu/facilities/vcc.html (accessed on 20 September 2021).
35. Tonguz, O.K.; Zhang, R. Harnessing Vehicular Broadcast Communications: DSRC-Actuated Traffic Control. *IEEE Trans. Intell. Transp. Syst.* **2019**, *21*, 509–520. [CrossRef]
36. Dresner, K.; Stone, P.A. Multiagent Approach to Autonomous Intersection Management. *J. Artif. Intell. Res.* **2008**, *31*, 591–656. [CrossRef]
37. Wei, H.; Zheng, G.; Gayah, V.; Li, Z. A Survey on Traffic Signal Control Methods, 2020. *Surv. Traffic Signal Control Methods* **2019**, *1*. [CrossRef]
38. Li, L.; Lv, Y.; Wang, F.Y. Traffic signal timing via deep reinforcement learning. *IEEE/CAA J. Autom. Sin.* **2016**, *3*, 247–254. Available online: https://www.academia.edu/28634266/Traffic_Signal_Timing_via_Deep_Reinforcement_Learning (accessed on 21 November 2021).
39. Mousavi, S.S.; Schukat, M.; Howley, E. Traffic light control using deep policy-gradient and value-function-based reinforcement learning. *IET Intell. Transp. Syst.* **2017**, *11*, 417–423. [CrossRef]
40. Zheng, G.; Xiong, Y.; Zang, X.; Feng, J.; Wei, H.; Zhang, H.; Li, Y.; Xu, K.; Li, Z. Learning Phase Competition for Traffic Signal Control. In Proceedings of the 28th ACM International Conference on Information and Knowledge Management, Beijing, China, 3–7 November 2019; pp. 1963–1972. [CrossRef]
41. Wang, X.; Ke, L.; Qiao, Z.; Chai, X. Large-Scale Traffic Signal Control Using a Novel Multiagent Reinforcement Learning. *IEEE Trans. Cybern.* **2021**, *51*, 174–187. [CrossRef] [PubMed]
42. Wei, H.; Zheng, G.; Gayah, V.; Li, Z. Recent Advances in Reinforcement Learning for Traffic Signal Control. *ACM SIGKDD Explor. Newsl.* **2021**, *22*, 12–18. [CrossRef]
43. Joo, H.; Ahmed, S.H.; Lim, Y. Traffic signal control for smart cities using reinforcement learning. *Comput. Commun.* **2020**, *154*, 324–330. [CrossRef]
44. Zhang, R.; Leteurtre, R.; Striner, B.; Alanazi, A.; Alghafis, A.; Tonguz, O.K. Partially Detected Intelligent Traffic Signal Control: Environmental Adaptation. In Proceedings of the 2019 18th IEEE International Conference on Machine Learning and Applications (ICMLA), Boca Raton, FL, USA, 16–19 December 2019; pp. 1956–1960. [CrossRef]
45. Zhang, R.; Ishikawa, A.; Wang, W.; Striner, B.; Tonguz, O.K. Using Reinforcement Learning With Partial Vehicle Detection for Intelligent Traffic Signal Control. *IEEE Trans. Intell. Transp. Syst.* **2021**, *22*, 404–415. [CrossRef]
46. Dezani, H.; Marranghello, N.; Damiani, F. Genetic algorithm-based traffic lights timing optimization and routes definition using Petri net model of urban traffic flow. *IFAC Proc. Vol.* **2014**, *47*, 11326–11331. [CrossRef]
47. Dezani, H.; Bassi, R.D.; Marranghello, N.; Gomes, L.; Damiani, F.; da Silva, I.N. Optimizing urban traffic flow using Genetic Algorithm with Petri net analysis as fitness function. *Neurocomputing* **2014**, *124*, 162–167. [CrossRef]
48. Sabar, N.R.; Kieu, L.M.; Chung, E.; Tsubota, T.; de Almeida, P.E.M. A memetic algorithm for real world multi-intersection traffic signal optimisation problems. *Eng. Appl. Artif. Intell.* **2017**, *63*, 45–53. [CrossRef]
49. Li, X.; Sun, J.-Q. Signal Multiobjective Optimization for Urban Traffic Network. *IEEE Trans. Intell. Transp. Syst.* **2018**, *19*, 3529–3537. [CrossRef]
50. García-Nieto, J.; Alba, E.; Carolina Olivera, A. Swarm intelligence for traffic light scheduling: Application to real urban areas. *Eng. Appl. Artif. Intell.* **2012**, *25*, 274–283. [CrossRef]
51. Zhang, Y.; Zhu, H.-B.; Liu, X.-Q.; Chen, X.-B. Optimal control for region of the city traffic signal base on Selective particle swarm optimization algorithm. In Proceedings of the 2017 36th Chinese Control Conference (CCC), Dalian, China, 26–28 July 2017; pp. 2723–2728.
52. Wijaya, I.G.P.S.; Uchimura, K.; Koutaki, G. Traffic light signal parameters optimization using particle swarm optimization. In Proceedings of the 2015 International Seminar on Intelligent Technology and Its Applications (ISITIA), Surabaya, Indonesia, 20–21 May 2015; pp. 11–16.
53. Baskan, O.; Haldenbilen, S. Ant Colony Optimization Approach for Optimizing Traffic Signal Timings. *Ant Colony Optim.—Methods Appl.* **2011**, *14*, 205–220. [CrossRef]
54. Renfrew, D.; Yu, X.-H. Traffic signal optimization using Ant Colony Algorithm. In Proceedings of the 2012 International Joint Conference on Neural Networks (IJCNN), Brisbane, Australia, 10–15 June 2012; pp. 1–7. [CrossRef]

55. Dell'Orco, M.; Baskan, O.; Marinelli, M. A Harmony Search Algorithm approach for optimizing traffic signal timings. *Promet—Traffic Transp.* **2013**, *25*, 349–358. [CrossRef]
56. Gao, K.; Zhang, Y.; Sadollah, A.; Su, R. Optimizing urban traffic light scheduling problem using harmony search with ensemble of local search. *Appl. Soft Comput.* **2016**, *48*, 359–372. [CrossRef]
57. Milanes, V.; Perez, J.; Onieva, E.; Gonzalez, C. Controller for Urban Intersections Based on Wireless Communications and Fuzzy Logic. *IEEE Trans. Intell. Transp. Syst.* **2009**, *11*, 243–248. [CrossRef]
58. Bi, Y.; Lu, X.; Sun, Z.; Srinivasan, D.; Sun, Z. Optimal Type-2 Fuzzy System For Arterial Traffic Signal Control. *IEEE Trans. Intell. Transp. Syst.* **2017**, *19*, 3009–3027. [CrossRef]
59. Moghaddam, M.J.; Hosseini, M.; Safabakhsh, R. Traffic light control based on fuzzy Q-leaming. In Proceedings of the 2015 International Symposium on Artificial Intelligence and Signal Processing (AISP), Mashhad, Iran, 3–5 March 2015; pp. 124–128.
60. Firdous, M.; Iqbal, F.U.D.; Ghafoor, N.; Qureshi, N.K.; Naseer, N. Traffic Light Control System for Four-Way Intersection and T-Crossing Using Fuzzy Logic. In Proceedings of the 2019 IEEE International Conference on Artificial Intelligence and Computer Applications (ICAICA), Dalian, China, 29–31 March 2019; pp. 178–182.
61. Hawi, R.; Okeyo, G.; Kimwele, M. Smart traffic light control using fuzzy logic and wireless sensor network. In Proceedings of the 2017 Computing Conference, London, UK, 18–20 July 2017; pp. 450–460. [CrossRef]
62. Hu, X.; Lu, J.; Wang, W.; Zhirui, Y. Traffic Signal Synchronization in the Saturated High-Density Grid Road Network. *Comput. Intell. Neurosci.* **2015**, *2015*, 1–11. [CrossRef]
63. Iyer, V.; Jadhav, R.; Mavchi, U.; Abraham, J. Intelligent traffic signal synchronization using fuzzy logic and Q-learning. In Proceedings of the 2016 International Conference on Computing, Analytics and Security Trends (CAST), Pune, India, 19–21 December 2016; pp. 156–161. [CrossRef]
64. Amogh, A.S.; Pujari, S.; Gowda, S.N.; Nyamati, V.M. Traffic timer synchronization based on congestion. In Proceedings of the 2016 International Conference on Computation System and Information Technology for Sustainable Solutions (CSITSS), Bengaluru, India, 6–8 October 2016; pp. 255–260. [CrossRef]
65. Khan, A.; Ullah, F.; Kaleem, Z.; Rahman, S.U.; Cho, Y.Z. Sensor-based self-organized traffic control at intersections. In Proceedings of the 2017 International Conference on Information and Communication Technology Convergence (ICTC), Jeju, Korea, 18–20 October 2017; pp. 634–638. [CrossRef]
66. Guler, S.I.; Menendez, M.; Meier, L. Using connected vehicle technology to improve the efficiency of intersections. *Transp. Res. Part C Emerg. Technol.* **2014**, *46*, 121–131. [CrossRef]
67. Sirikham, A. Development of a Wireless Stop Light Synchronization System for Single-lane Traffic Control. In Proceedings of the 2021 18th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), Chiang Mai, Thailand, 19–22 May 2021; pp. 1006–1009. [CrossRef]
68. Kumar, D.M.; Arthi, R.; Aravindhan, C.; Roch, A.A.; Priyadarsini, K.; Deny, J. Traffic Congestion Control Synchronizing and Rerouting Using LoRa. *Microprocess. Microsyst.* **2021**, 104048. [CrossRef]
69. Reddy, K.S.; Shabarinath, B. Timing and Synchronization for Explicit FSM Based Traffic Light Controller. In Proceedings of the 2017 IEEE 7th International Advance Computing Conference (IACC), Hyderabad, India, 5–7 January 2017; pp. 526–529.
70. Khedkar, A.; Kumar, V. Self synchronization based air traffic control and collision avoidance system. In Proceedings of the 2011 IEEE/AIAA 30th Digital Avionics Systems Conference, Seattle, WA, USA, 16–20 October 2011; pp. 1–8. [CrossRef]
71. Wu, J.; Yan, F.; Kuang, P. Distributed urban traffic signal control based on spontaneous synchronization. In Proceedings of the 17th International IEEE Conference on Intelligent Transportation Systems (ITSC), Qingdao, China, 8–11 October 2014; pp. 2202–2207. [CrossRef]
72. Adacher, L.; Tiriolo, M. A Distributed Approach for Traffic Signal Synchronization Problem. In Proceedings of the 2016 Third International Conference on Mathematics and Computers in Sciences and in Industry (MCSI), Chania, Greece, 27–29 August 2016; pp. 191–196.
73. Adacher, L. A Global Optimization Approach to Solve the Traffic Signal Synchronization Problem. *Procedia—Soc. Behav. Sci.* **2012**, *54*, 1270–1277. [CrossRef]
74. Aleko, D.R.; Djahel, S. An IoT Enabled Traffic Light Controllers Synchronization Method for Road Traffic Congestion Mitigation. In Proceedings of the 2019 IEEE International Smart Cities Conference (ISC2), Casablanca, Morocco, 14–17 October 2019; pp. 709–715.
75. Nesmachnow, S.; Massobrio, R.; Arreche, E.; Mumford, C.; Olivera, A.C.; Vidal, P.J.; Tchernykh, A. Traffic lights synchronization for Bus Rapid Transit using a parallel evolutionary algorithm. *Int. J. Transp. Sci. Technol.* **2019**, *8*, 53–67. [CrossRef]
76. Cabezas, X.; García, S.; Salas, S.D. A hybrid heuristic approach for traffic light synchronization based on the MAXBAND. *Soft Comput. Lett.* **2019**, *1*, 100001. [CrossRef]
77. Adacher, L.; Gemma, A.; Oliva, G. Decentralized Spatial Decomposition for Traffic Signal Synchronization. *Transp. Res. Procedia* **2014**, *3*, 992–1001. [CrossRef]
78. Rodriguez, M.; Fathy, H. Self-Synchronization of Connected Vehicles in Traffic Networks: What Happens When We Think of Vehicles as Waves? In Proceedings of the 2019 American Control Conference (ACC), Philadelphia, PA, USA, 10–12 July 2019; pp. 2651–2657. [CrossRef]

79. Astarita, V.; Festa, D.C.; Giofre, V.P. Cooperative-Competitive Paradigm in Traffic Signal Synchronization Based on Floating Car Data. In Proceedings of the 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Palermo, Italy, 12–15 June 2018; pp. 1–6.
80. Yingxiang, Y.; Min, Y.; Lei, S.; Jian, S.; Yong, W. Traffic Signal Synchronization of a Small Urban Network Using Cellular Automaton. In Proceedings of the 2011 Third International Conference on Measuring Technology and Mechatronics Automation, Shanghai, China, 6–7 January 2011; Volume 3, pp. 1035–1039.
81. Li, Z.; Ding, Z.; Wang, Y.; Fu, Y. Time synchronization method among VANET devices. In Proceedings of the 2017 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET), Chennai, India, 22–24 March 2017; pp. 2096–2101.
82. Abbasi, M.; Shahraki, A.; Barzegar, H.R.; Pahl, C. Synchronization Techniques in "Device to Device- and Vehicle to Vehicle-Enabled" Cellular Networks: A survey. *Comput. Electr. Eng.* **2021**, *90*, 106955. [CrossRef]
83. Du, W.; Abbas-Turki, A.; Koukam, A.; Galland, S.; Gechter, F. On the V2X speed synchronization at intersections: Rule based System for extended virtual platooning. *Procedia Comput. Sci.* **2018**, *141*, 255–262. [CrossRef]
84. Tomar, I.; Indu, S.; Pandey, N. Traffic Signal Control Methods: Current Status, Challenges, and Emerging Trends. In *Proceedings of Data Analytics and Management*; Springer Science and Business Media LLC: Singapore, 2022; Volume 90, pp. 151–163.