A survey on smart traffic network control and optimization

(Invited Paper)

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***Abstract*—In the current day and age, traffic in urban areas is becoming more and more complex leading to congested roads and intersections. Hence, the need for sophisticated traffic control system to reduce the congestion and provide better flow management. In this paper, we present briefly the basic notions and the most important parameters that affects the traffic control. Then, we provide a survey on the main flow management systems that are available in the literature. Some possible future research works and propositions on intelligent traffic control are also provided.**

***Index Terms*—Traffic control, optimization, WSN, intelligent traffic control systems.**

I. Introduction

Traffic networks are becoming more and more complex and tedious due to the large amount of vehicles on the roads and limited capacities of the latter. This leads to congestion and traffic jams that consequently has a non-negligible impact on economy, environment and human health. According to Transport Statistics Great Britain 2015[1], for example, all major roads combined together accounted for 13% of road length and carried 65% of total road traffic, while minor roads made up 87% of road length but carried 35% of traffic. These figures clearly indicate that it is more likely to get traffic jams or congestion in urban areas. On the other hand, the old methods of traffic management and facilities had become less efficients and obsolete due to several factors; namely, increasing number of vehicles on the roads, growing population and economies. There is, therefore, a real incentive to develop new traffic management system to cater for these factors. On of the promising ways to control and manage such large amount of traffic, especially in urban or metropolitan areas, is the so-called Internet of Things (IoT). In this context, using a WSN (Wireless Sensor Network) to control traffic is more efficient in many areas. Experiments in [2] shows that a network of wireless magnetic sensors offers much greater flexibility and lower installation and maintenance costs than inductive loop, video and radar detector systems. Additionally, sensor nodes in WSN are small size, energy efficient and are easy to deploy in different locations and parts of the roads. This last feature enables sensor nodes to easily measure the traffic loads and information in the whole road [3].

In this paper we are going to give an overview of smart traffic network control. The main motivation is to give an evaluation and assessment of the problems related to traffic control and of the realized works in this matter. This paper is organized as follows: in Section 2 we discuss the standard traffic control systems and modeling-problem statement. In Section 3 we present and analyze some projects, methodologies and approaches about traffic control. Finally, we end the paper with a discussion and some concluding remarks.

II. Standard traffic control systems and modeling problem statement

In this section, we are going to define and to describe the basic notions and parameters of traffic control and lights management, also to mention some hazards that could unintentionally affects the traffic at any point of the road. The most important parameters and varaibles to consider are as follow[4] [5].

1) *Signal cycle* is the repetition of the signal combinations, its duration is a known as "*cycle time*".
2) A *stage* (or *phase*) is a part of the signal cycle, during which one set of streams can move securely.
3) *Split* is the green duration of each stage that should be optimized according to the demands.
4) *Offset* is the phase difference between cycles for successive intersections that may give rise to a "green wave" along an arterial; clearly, the specification of offset should ideally take into account the possible existence of vehicle queues.

In daily life some hazards may occur and affect heavily the traffic (usually causing a congestion), these hazards can be for example fallen trees due to the wind, accidents, broken bridge, potholes, narrow lanes ...etc. Each intersection has its

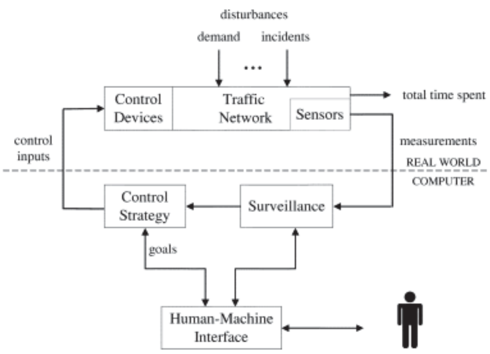

Fig. 1. The control loop [5]

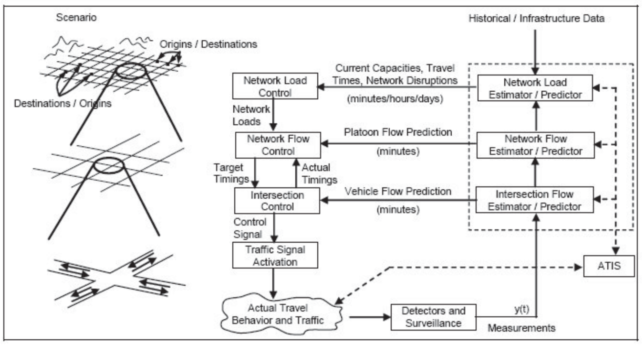

Fig. 2. The RHODES hierarchical architecture [6]

own number of lanes for each approach (road) leading to the intersection. Some works[6] [10] [13] [17] consider an intersection with only one lane for all vehicles, while some others consider a lane for each direction (a lane for vehicles going forward, another one for vehicles turning right and another one for vehicles turning left). This has a great impact on the algorithm to be used in scheduling the lights and in the number vehicles in conflict.

III. Literature review on the methodologies and approaches for traffic control

The main purpose of installing traffic lights at an intersection is to organize the flow of vehicles passing through it and to avoid collision, by stopping vehicles in some lanes and allowing other lanes' vehicles to go through the intersection. As a result, queue lines appear and congestion are likely to occur whenever there is a large influx of vehicles. Hence, the need of optimization of these traffic lights in order to minimize queues lengths and waiting time, on one hand, and to maximize the fluidity of the traffic around the intersection on the other.

Many researchers have worked on this topic with different approaches and objectives by considering one of the following two aspects: single (isolated) intersection or interconnected intersection. Review of Road Traffic Control Strategies[5] highlights the basic notions and describes the different strategies of traffic control. It also classify them according to several criteria such as coordinated trafficresponsive strategies, fixed-time coordinated or isolated intersection control.

According to this review [5], there are many problems and constraints that affect the control loop depicted in Figure 1:

- The red-green switchings of traffic lights call for the introduction of discrete variables, which renders the optimization problem combinatorial.
- The size of the problem for the whole network is very large.
- Many unpredictable and hardly measurable disturbances (incidents, illegal parking, pedestrian crossings, intersection blocking, etc.) may perturb the traffic flow.
- Measurements of traffic conditions are mostly local (via inductive loop detectors) and highly noisy due to various effects.
- There are tight real-time constraints, e.g. decision making within $2s$ for advanced control systems.

Meanwhile, there are four possibilities for influencing traffic conditions via traffic lights operation:

i) Stage specification
ii) Split (the relative green duration of each stage -as a portion of the cycle time- that should be optimized according to the demand of the involved streams)
iii) Cycle time and
iv) Offset(the phase difference between cycles for successive intersections that may give rise to a "green wave" along an arterial).

In [6] the authors discussed a real-time traffic-adaptive signal control system, known as RHODES, which takes input from the different kind of sensors for real-time measurement of traffic flow then predicts the traffic stream, both spatially and temporally. The system optimally controls the flow through out the network according to the following steps:

1) Decomposes the traffic control problem into interconnected subproblems.
2) Predicts traffic flows at appropriate resolution levels.
3) Allow various optimization modules for solving the hierarchical subproblems.
4) Uses a data-structure and computer processing for fast problem solving.

The city and road architecture are considered as adjacent squares, where the traffic lights are installed in every intersection and sensors in each road to predict vehicles going left (l), right (r) or through (t). The sensors are implemented at a distance from the lights so it allows to have enough time (before the vehicles reach the intersection) to make the prediction and the combination with other intersections.

The RHODES architecture for surface streets is depicted in Figure 2 [7]. As shown, the system operates in three hierarchical levels: Network Load Control, Network Flow Control and Intersection Control level.

When a vehicle passes a detection point d_i at intersection B

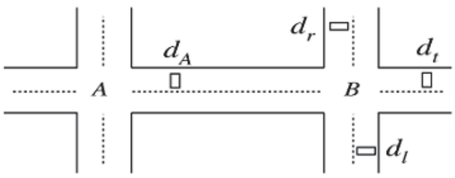

Fig. 3. Prediction scenario based on detectors on the approaches to the upstream intersection (B)[6]

(see Figure 3) where $i \in \{l, r, t\}$ several factors affects when it will arrive at the next intersection A detector (d_A), mainly:

- The travel time from detector, d_i, to the stop bar at intersection B;
- The delay due to an existing queue at B;
- The delay due to the traffic signal at intersection B;
- The travel time between B and the intersection A detector d_A.

The PREDICT model [8], which is used to predict the arrivals in term of time essentially, needs several parameters to be provided and which are:

- Traffic times on links, which depends on link free-flow speed and current traffic volume;
- Queues discharge rates, which depends on volume as well as on queue spill backs and opposing and cross-traffic volume;
- Turning probabilities;
- Estimates of queues at the intersections to estimate arrivals and demand for various phases of the lights.

In real life and in real-time traffic measurement these parameters are not deterministic, they change over time. The authors in this work[6] have developed a simple algorithm to estimate the queue length. Suppose at the beginning of a green phase, say at time t_0, our initial queue estimate at some stop-bar is $q(t_0)$. At the end of green phase, say at t_1, the remaining queue $q(t_1)$ is given by

$$q(t_1) = q(t_0) + a(t_1, t_0) - d(t_1, t_0) \quad (1)$$

where $a(t_1, t_0)$ is the number of predicted arrivals between t_1 and t_0, and $d(t_1, t_0)$ is the predicted number of departures (using a given queue discharge rate). The system uses a time horizon of $20 - 40s$ to predict the arrivals and queues in each intersection (Intersection Control level), and a time horizon of $200 - 300s$ in the Network Flow Control level.

At the Intersection Control level, RHODES uses a dynamic programming based algorithm, this latter is decomposed on many stages and each stage is associated with a signal phase. At the Network Flow Control level, the control logic is based on a model called REALBAND [9]. The idea behind this model is to consider platoons (characterized by number of vehicles and speed). When two or more platoons are predicted to arrive at an intersection and a conflict occurs, a decision tree is made where each branch of this tree represents one possible solution of the conflict. The decision tree developed is based on the predicted platoon movement over some predefined horizon, such as $200 - 300s$. The best solution to consider is the one with best-estimated performance (the performance in this system is defined in term of the shortest delay of waiting).

The software designed to process the data and execute the algorithm is simple and is centered around a database and an executive command controller. The database contains all relevant network and control information, which is of three types: dynamic data, model parameters, and statistic data. Dynamic data refers primarily to data that changes on a second by second basis. Model parameters data refers to information that is either constant or changes slowly over time such that only the current value is relevant and the time-trajectory (past and future) is less relevant. Statistic data includes values that are assumed to remain constant -network geometrics (node ID numbers, number of lanes on each road, link lengths ...etc.) are the primary types of static data[6].

RHODES shows two important features: slightly better throughput and significant delay decrease. The average vehicle delays decrease in the range of 50% for low loads to 30% for high loads. In the high load case, not only are the average delays smaller, but also the variance of the delay is significantly reduced.

In [10] an intelligent traffic light flow control system using WSN is proposed. The idea behind this system is to use WSN and two algorithms to manipulate the light duration of both red and green, which are TSCA (Traffic System Communication Algorithm) and TSTMA (Traffic Signals Time Manipulation Algorithm). The WSN consists of Traffic Sensors Nodes (TSN) which are installed in the roadbed in a patholes in the streets, in each lane of the roads. The roads and the intersection model considered in this work is as follows: four paths leading to the intersection, each path is divided into three lanes (right turn, left turn and going forward), we have in total twelve lanes (twelve possibilities) operating.

The sensors are connected to a Base Station (BS) and the BS is connected to a Traffic Control Box (TCB). Sensors (TSNs) collect, generate and transmit parameters and data to the BS. These main parameters and data, among many others, are the arrival rates of vehicles (λ_i) of each lane, departure rates (μ_i) and the queues lengths of each lane also (Q_i).

The intersection is viewed as a M/M/1 model of twelve queues, each queue with its own λ_i, μ_i and Q_i. Based on the queues' lengths, the algorithm performs many operations and scenarios each T cycle, where $15s \leq T \leq 90s$ and is set separately for each scenario. The scenarios are generated from the possible combinations, those with safe lanes, and the situation with the higher sum of queues length is prioritized.

This work proposes as well the extension of the two algorithms TSCA and TSTMA to work on multiple intersections to coordinate their traffic flows.

Barba et al. presented in [11] a system based on vehicles' messages, where ITL (Intelligent Traffic Lights) communicate with vehicles to avoid congested intersections due to an accident for example. They focused on the analysis of traffic density as the most important criteria to make decisions.

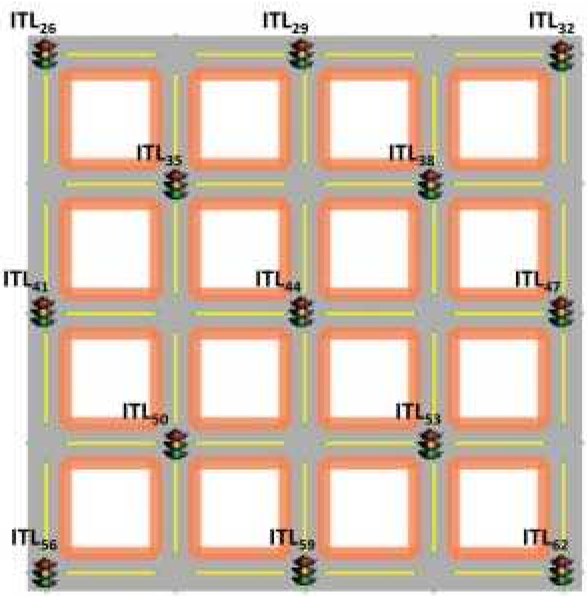

Fig. 4. Intelligent Traffic Light distribution [11]

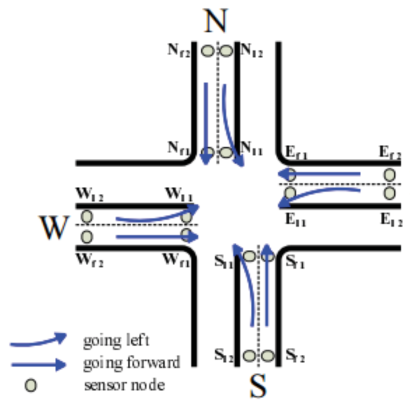

Fig. 5. Isolated intersection [12]

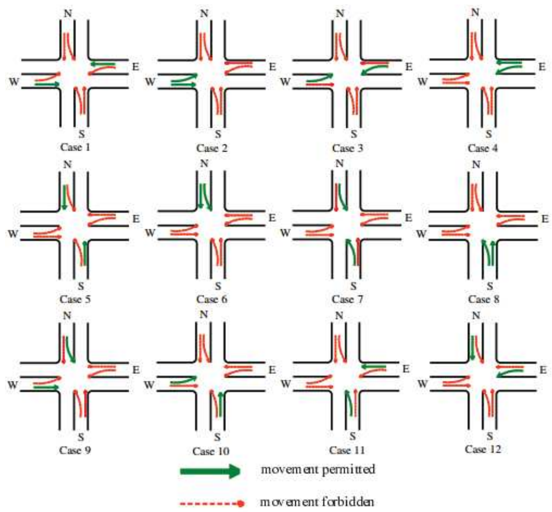

Fig. 6. Twelve possible configurations of green lights[12]

The city is composed of square blocks in this work, and it is not necessary to have ITL in every intersection. In fact each ITL in an intersection covers four streets leading to it as shown in Figure 4.

In every two seconds messages are sent from vehicles to ITLs, containing among others the vehicle ID and number of neighbors, the time it was sent and ITL IP address. Statistics are shared between the ITLs, then each ITL will send back to each passing vehicle an updated message about traffic statistics of the city. With this information, the driver's assistant device can take proper trip decisions (e.g. avoiding congested roads) [11], assuming that vehicles have a global positioning system (GPS) device, a driver assistant device and a full map of the city including the position of the ITLs.

The paper does discuss a smart city concept where many fields and domains are concerned like parkings, VANETs, ITLs, etc., but authors didn't present any algorithm of communication or optimization.

In addition, the most important issue to deploy such a system is that we cannot make every vehicle on the road today equipped with GPS, driver assistant device and other sensors. Furthermore, the cities in reality are not all of the Manhattan style characterized by adjacent square blocks as shown in Figure 4.

The adaptive traffic light control algorithm proposed in [12] adjust both the sequence and the length of traffic lights in accordance with real-time traffic detected. The efficiency or performance in this work is considered in terms of "maximum intersection throughput (number of vehicles passing through the intersection)" and "minimum vehicles average waiting time".

The authors considered the use case road model as an intersection with four directions (North: N, South: S, East: E, West: W), each of which has two lanes to go, one for going forward and the other for turning left. Each lane is controlled with a traffic light that offers two signals: Red or Green. Each lane is equipped with two sensors: one at the intersection and the other one is installed a distance $SensorsDistance$ away from the intersection (Figure 5).

According to this model, there exists twelve possible cases of green lights without any conflict as shown in Figure 6.

The problem is then transformed to decide with case should obtain green light next and for how long it should lasts.

Assuming that the vehicles run at constant speed speed, the algorithm contains three main steps: vehicle detection, green light sequence determination, light length determination.

The problem with the vehicles detection approach used is that it is perfect and not suitable for real environment because it doesn't reflect the real life events as they occur really. In fact, they calculate the arrival rate and departure rate using the sensed data by sensors. Lanes are divided into several intervals with arrival and departure rate for each interval, such that arrival rate in D_i at time t is equal to the departure rate in D_{i+1} at time $t-1$. An interesting optimization trick here is that when there is a gap or a blank in the flow, the blank should arrive at the intersection at a red light, so the green light, which is a valuable resource, is not wasted (i.e. light is green and no car passing).

In order to decide the green light sequence determination, authors define a function $GLD(k,t)$ to indicate the k's green light demand at time t, such that the case with the most urgent demand should get the next green light. Many factors have an impact on this decision described:

$$\begin{aligned} GLD(k,t) &= a_1TV(k,t) + a_2WT(k,t) \\ &\quad +a_3HL(k,t) + a_4BC(k,t) \\ &\quad +a_5SC(k,t) + a_6Nbr(k,t) \end{aligned} \quad (2)$$

Here, $TV(k,t)$, $WT(k,t)$, $HL(k,t)$, $BC(k,t)$, $SC(k,t)$, $Nbr(k,t)$ are defined as the weight of Traffic Volume, average Waiting Time, Hunger Level, Blank Circumstance, Special Circumstance and influence from Neighboring intersections of case k at time t, respectively, a_i are defined as the coefficient of these parameters to demonstrate their priorities, $i = 1, 2, 3, 4, 5, 6$. They ignored $Nbr(k,t)$ since the distance between two intersections is longer than $SensorDistance$. This $GLD(k,t)$ definition is very pertinent and it gathers real life factors, so the demand equation is well formulated. The factors formulas are defined in the paper one by one for more details. Moreover, the presented algorithm gives an idea how coefficients are treated and how to determine the most priority case.

In this paper the authors defined G_{next} as the length of next green light, it is equal to the time for vehicles in lanes having next green light to go through the intersection. G_{next} has an upper bound that mustn't be surpassed and defined or based on expert knowledge [12].

The system has been compared with the most used approaches fixed-time and actuated traffic light, it outperforms them in both throughput and average waiting time in different roads saturation degrees.

Chen et al. [13] proposed a new vehicle detection method, using Wireless Sensor Network (WSN) technology, and developed a new signal control algorithm to control the state of the signal light in a road intersection. They took on a model of four approaches: N (north), S (south), E (east) and W (west). Each approach has three lanes: L (left), F (Forward) and R (right). Every vehicle is represented by a pair of $\{\eta, \theta\}$ where $\eta \in \{N, E, W, S\}$ and $\theta \in \{L, F, R\}$. In addition they assume that right turns are permitted all time since they don't present any conflict with other lanes, except in case of pedestrians crossing the road where they have the priority according to an exception rule.

The signal cycle is divided into four phases as depicted in Figure 7.

The advantage of such system is that is takes into consideration the pedestrians crossing the streets in phase (a) and (c). The algorithm is designed to adjust the duration for each phase between 15 and 90 seconds, depending on the vehicles conditions detected, and is demonstrated in this paper.

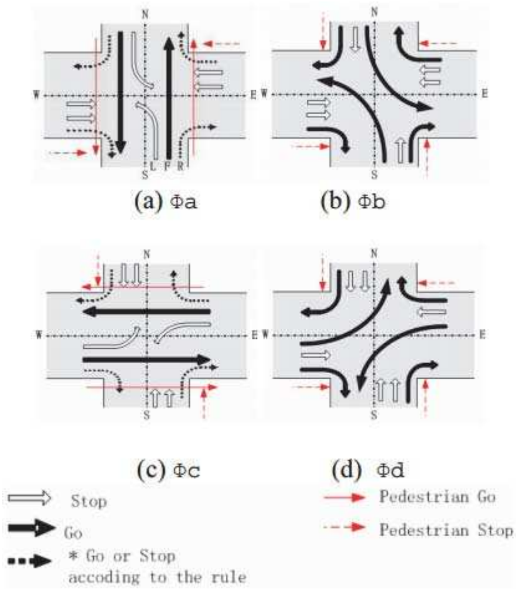

Fig. 7. Four phases of signal light[13]

There are three types of sensors and nodes used in this work: control node at the intersection, detector nodes installed on the streets and vehicle nodes installed on vehicles. Installing nodes on vehicles allows also to identify Emergency vehicles with electronic tags to detect them and their (η, θ) in order to give them the priority on the road as detailed in this paper.

The advantages presented in this work are the taking into account of the cyclists and pedestrians, also the emergency vehicles. Meanwhile, installing detectors in every vehicle on the road is not realistic and not conceivable for now. Furthermore, the signal light is 4-status finite state machine and it shifts from among pre-defined phases (a), (b), (c) and (d).

Collotta et al. [15] considered the reduction of the average waiting time as the main aim of their work. The dynamic management algorithm they used is can be described in two parts: phase sequence determination and green time calculation. In fact, the algorithm, based on the queue length for each flow (input variable), assigns a priority to each phase equal to the maximum queue length of that phase. The work was based on the intersection model shown in Figure 8, and they considered two scenarios of phases as shown in Figure 9.

The two scenarios differ by traffic volume. Scenario 1 has high traffic and scenario 2 has reduced cross-street traffic. Such a system outperforms static management algorithms as seen in the results of comparison.

The work [16] of Marco et al. doesn't use a cycle, but let the decision depends on the actual traffic situation around a junction. The ideal situation (the goal) is the state where there are no cars waiting (i.e. $waitingtime = 0$). The used a voting system where each car votes using its estimated advantage (or gain) of setting its light to green. Each car is represented or identified as follows: is at a specific traffic $node$, a $direction$ at that node (dir), a $position$ in the queue

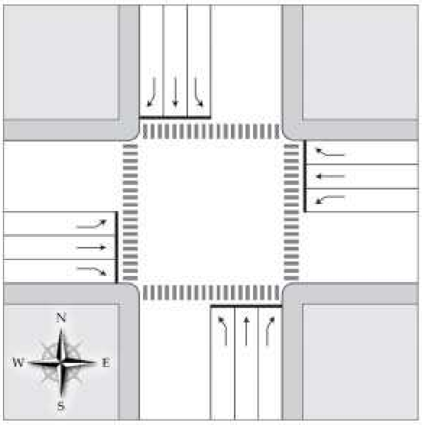

Fig. 8. Examined intersection[15]

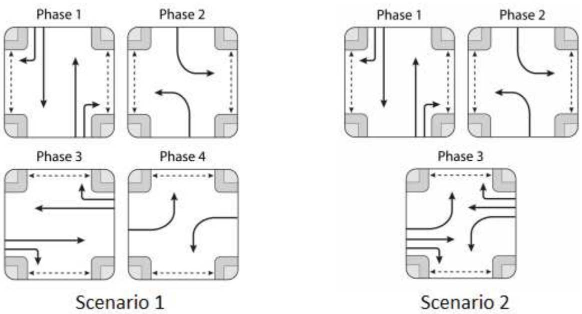

Fig. 9. Traffic signal phases phasing plan for scenarios 1 and 2[15]

($place$) and has a particular $destination$ address(des), that make the identification (n, d, p, des). The authors used also a probabilistic approach combined with the voting system to determine the probability for a car that the light is red or green at a specific place with some direction.

In this work, every junction is controlled by a traffic light controller (TLC) that can share information with other controllers to improve global performance. Many controllers (algorithms) have been used and not only one.

The most notable advantage of this system is that the decisions are made in real-time and according to the current situation without any constraint on the cycle. This give the system the entire flexibility to adjust the lights and their corresponding timing length.

Meanwhile, the paper doesn't mention which controller is used in each intersection or only one controller for the whole system. Also, treating each node (vehicle) of the system separately, and then together with other nodes, makes the number of situations huge. Furthermore, this approach requires a lot of data processing.

IV. Concluding remarks and future works

In this work, we have seen some works on intelligent traffic lights where researchers used WSN, simple sensors and/or analytic approaches to regulate the traffic around an intersection. We have also presented a survey on each road and intersection model used in each work and have seen how it influences the global system and the decision to be taken, for both single and interconnected intersection. We can conclude that each system has its own advantages and weakness, and that future works should build upon studies similar to this in order to use and combine the benefits of previous works to create a better traffic management system.

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