INTERNATIONAL JOURNAL OF COMPUTERS COMMUNICATIONS & CONTROL
Online ISSN 1841-9844, ISSN-L 1841-9836, Volume: 17, Issue: 4, Month: August, Year: 2022
Article Number: 4866, https://doi.org/10.15837/ijccc.2022.4.4866

CCC Publications

Optimization of Road Traffic Using Intelligent Traffic Light Systems

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Abstract

If we consider road traffic in urban areas, one of its major problems encountered nowadays is that of traffic congestion. The paper aims to provide an improvement, in terms of reducing traffic congestion, by analyzing different traffic light cycles. A traffic light cycle is determined by the red and green duration of the traffic lights. Traditionally these two have a fixed duration and controlling road traffic can be achieved by modifying it, resulting in a congestion reduction. We present a comparison between the fixed and an improved fixed situation, as well as a QL algorithm to further reduce the congestion at an intersection. Urban traffic can thus be optimized, in terms of reducing congestion, on an existing traffic light system. A study case validates the results, based on road traffic data obtained from the city of Bucharest.
Keywords: Traffic lights, Traffic congestion, Optimization.

1 Introduction

As the automotive industry has grown exponentially beyond the pace of road infrastructure development, modern traffic problems have become major concerns around the world today.

There have been concerns about how to model and control traffic for almost a century. The first studies date back to the 40s and 60s. The first study considered traffic as a stochastic system and used probability theory to describe the behavior of traffic flow [1]. In 1950, new studies were developed based on theoretical approaches such as tracking vehicles in circulation [2], traffic flow theory [4, 5] and queue theory [6]. In 1970 a new approach was introduced, based on the analogy with the flow of liquids in fluid mechanics; Payne and Whitham can be mentioned as precursors [7, 8].

In recent decades, traffic theory has undergone significant developments, with authors trying to improve existing models or propose new ones, appropriate to the new traffic conditions. An analysis of the main types of models used to describe the dynamics of road traffic was made in [9].

Lately, developements have been made to control traffic by making use of Artificial Intelligence(AI) to build Intelligent Traffic Lights Controllers [10]. A very good method that has application in this area is Reinforcement Learning which uses Q-learning algorithms to optimize the waiting time at traffic lights [11]. By combining AI and IoT the information from neighboring intersections can be taken into account [12].

In this context, the paper aims to improve urban road traffic, by optimizing the use of efficient traffic light systems. The main aim is to decongest the intersections and to assure the flow of traffic in crowded networks, through adaptive and intelligent actuation mechanisms implemented on the traffic light systems. The novelty of the solution is given by the possibility of implementing on existing infrastructures control and actuation systems, destined to the surveillance of urban traffic, with the resources provided by new intelligent technologies. The optimization in this paper refers to the decrease of the traffic congestion in the intersections, at each traffic light cycle, by using the QL algorithm that updates in real time the durations of the traffic light according to the number of existing cars.

The paper is organized in 5 chapters. After the introduction, the second chapter introduces aspects related to the phenomenon of road congestion and presents the main types of existing traffic light systems. Chapter 3 details the traditional traffic light mechanism, with a fixed period for a traffic light cycle and improved fixed period, which increases the green color with priority, presenting its advantages and disadvantages compared to fixed traffic lights. A software simulator structure is used for the study of the behavior of various types of traffic light systems. Chapter 4 develops the advantages of intelligent traffic lights and proposes an intelligent machine learning method, based on the efficiency offered by the Reinforcement Learning (QL) algorithm in solving control and optimization problems. The performance of the intelligent traffic light method in optimizing urban traffic is estimated and confirmed using a dedicated simulator. Chapter 5 presents a case study to illustrate and validate the results obtained in the simulation on a physical traffic network and recommends the use of intelligent traffic light systems to optimize road traffic. Finally, conclusions are given to justify the need and objective of the research and the quality of the results. As a perspective, it is recommended to implement the intelligent solution on a physical traffic network with real-time interaction with the existing traffic light system.

2 Congestion and traffic light systems

2.1 Traffic congestion

Traffic congestion is one of the most worrying problems of the modern world, which desires to satisfy the need for unhindered mobility. It is the price paid for the multiple benefits arising from the concentration of population and economic activities. Since the supply of land is exhausted and the development of road infrastructure is expensive, it would not be profitable to invest to achieve capacities to permanently provide traffic regimes close to the free regime. Even if for the time being, by developing infrastructure, this regime would be achieved, as traffic demand depends on the overall social cost it means that at the same time the effects of stimulating demand will inevitably lead to a new traffic regime. As a compromise, the solution remains to use existing road infrastructure and find control solutions to assure traffic flow and prevent congestion.

In **Fig. 1** we can see the effects of congestion on traffic flow. The congestion of section I affects sections II and III: the white circles are vehicles stuck due to the congestion of section I; the grey circles are vehicles which, due to lack of space in section I, are unable to continue their journey on the routes indicated; the black circles are vehicles blocked due to front vehicles that can no longer continue to move.

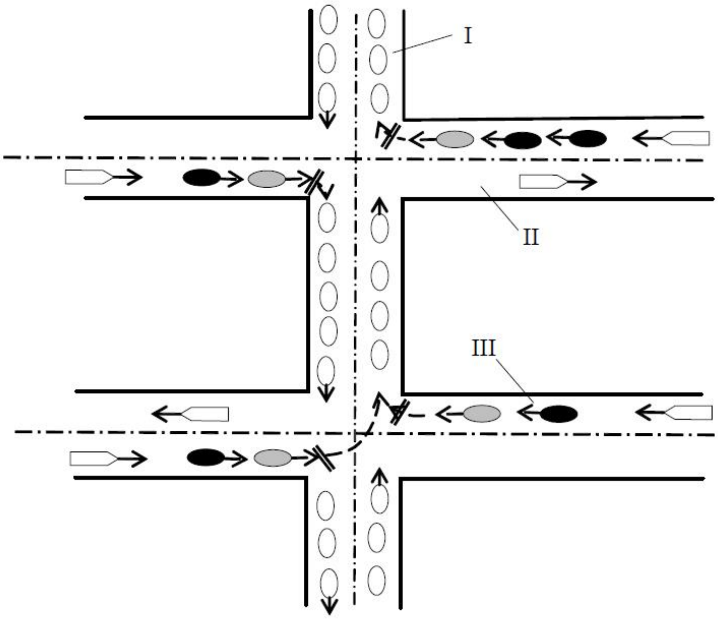

Figure 1: Effects of traffic congestion.

2.2 Traffic light systems

We considered a cross type intersection, represented in **Fig. 2**. In an intersection there are four traffic lights a, b, c and d (for each direction). On the ab direction the traffic lights a and b are synchronized (they have the same durations of green and red), analog for cd. When the ab direction is green, the cd direction will be red and vice versa. Usually, we will only calculate the green times for each direction, because the red time will be the green time calculated for the next direction.

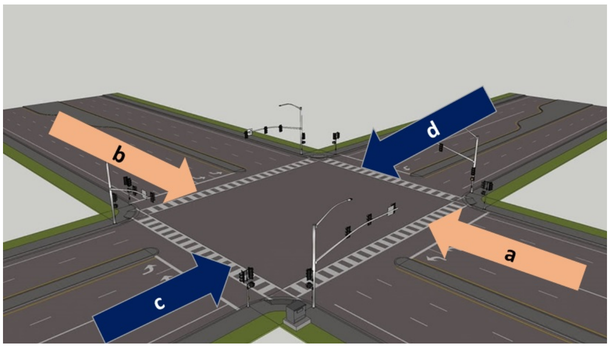

Figure 2: Intersection with two routes: ab and cd

There are two types of approaches when it comes to traffic light systems: the classical fixed time approach used in many cities around the world and the modern variable time approach. These approaches are related to the traffic light cycle, which represents the sum of the duration of green and the duration of red. Taking into account these approaches there are the following traffic light methods:

1. Fixed cycle traffic light: in this type of traffic light the duration of green is equal to the duration of red (T) and cycle time is constant (2T). As can be seen in **Fig. 3** traffic lights ab and cd have fixed values of traffic light times. The duration of green or red does not depend on the number of cars waiting in traffic.

2. Improved fixed cycle traffic light: the traffic light is set to increase (2T) the green time in some crowded moments only on the artery with heavy traffic, then to return to the default value. Red time on the adjacent sense will be equal with green time improved (2T). (**Fig. 3**)

3. Intelligent cycle traffic light: assumes that green and red times are calculated for each cycle using an algorithm that considers the number of cars waiting in line at the intersection. The green and red times are complementary and variables between the arteries. Also, the traffic light cycle is variable (e.g. different values T1 -T4 in **Fig. 3**.

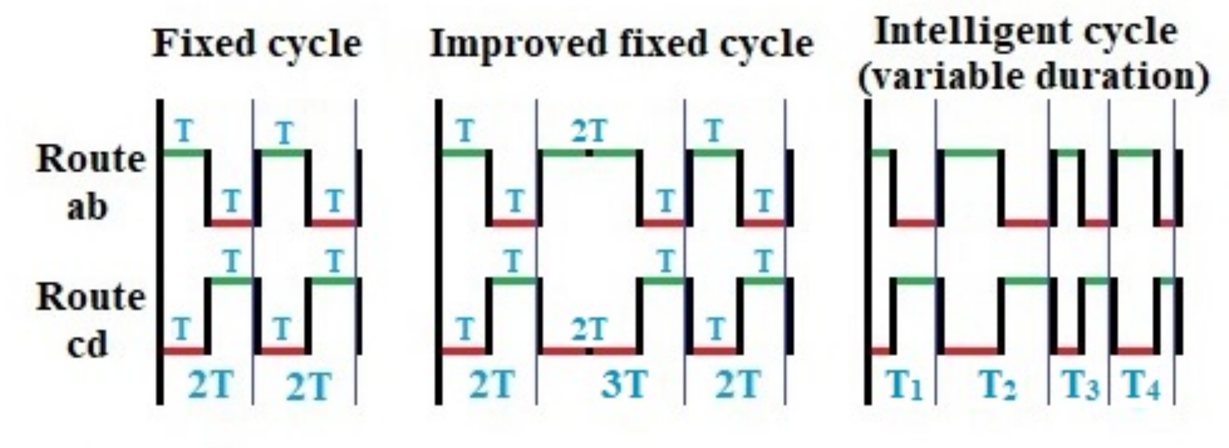

Figure 3: Fixed, improved fixed and intelligent cycle traffic light: green - green time, red - red time, blue - cycle period

3 Fixed and improved fixed traffic lights

In this section we will consider both congested routes (ab and cd) for which there is a peak traffic profile. The traffic values in this section were randomly generated between certain intervals using a software module. We will apply the improved fixed traffic light, i.e. on the ab route we will increase the duration of the green traffic light by half of its initial value at rush hour. As can be seen in **Fig. 3** green and red time are complementary. That is, the increase of the green time on ab (2T) will determine consequently the increase of the red time on cd (2T) which will lead to an increase of the traffic light cycle (3T). We will keep the usual green time for cd (T) which will be reflected in the red time on ab (also T). When we no longer have rush hour traffic, we decrease the green time on the ab from 2T to T which will lead to a shorter red time for the cd (also T). For the congested artery ab (after adding the number of cars on a and b) the fact that we introduced the improved fixed traffic light reduced the congestion because the number of cars waiting at the red light departed at the first green light (in **Fig. 4** we can see that the blue graph is almost overlapping with the red one). If we increase the green time at certain moments on the ab artery, we notice that there is a number close to zero of the cars that would overcrowd the intersection (the green graph has very small values) and thus we can control the traffic on this artery very well.

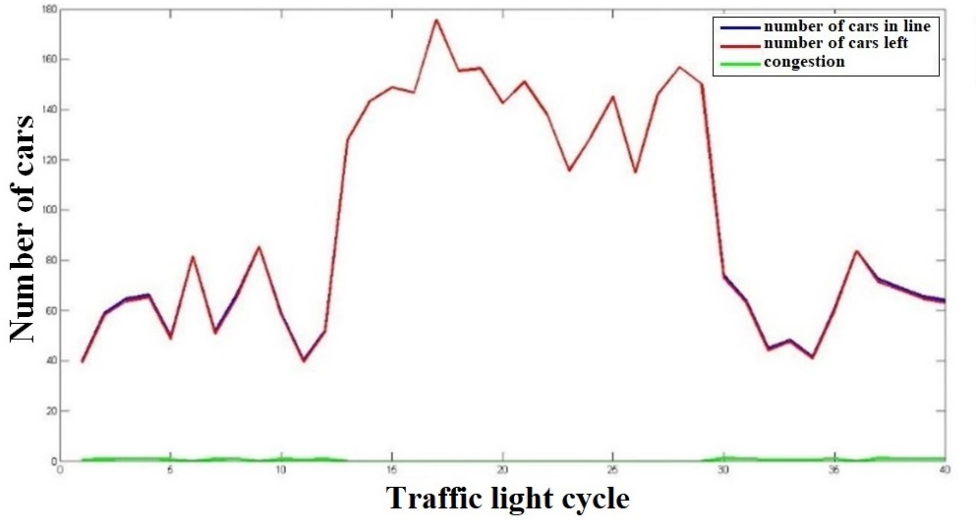

Figure 4: Improved fixed traffic light ab: Number of cars on the ab route cumulated in both directions (blue-number of cars in line; red-number of cars left; green-number of cars that caught the second red light); Traffic light time: Green time in general: 55 s, Green time at rush hour 82.5 s, Red time: 55 s.

On the opposite direction cd in **Fig. 5**, it can be seen that the improved fixed method introduces blockages: in the moments when spikes appear (axis cycle 13, 17, 20, 21, 25) agglomerations are formed, due to the fact that there will be a significant number of cars, which will remain at least two red lights (for instance, when there are 180 cars in traffic). Cars waiting in line will not go in the same traffic light cycle (the blue graph does not overlap the red one). From the two **Fig. 4** and **Fig. 5** it can be seen that the use of improved fixed traffic lights, in which we increase the green time for a certain direction, will decongest the traffic only in that direction, and in the opposite direction it will be formed congestions.

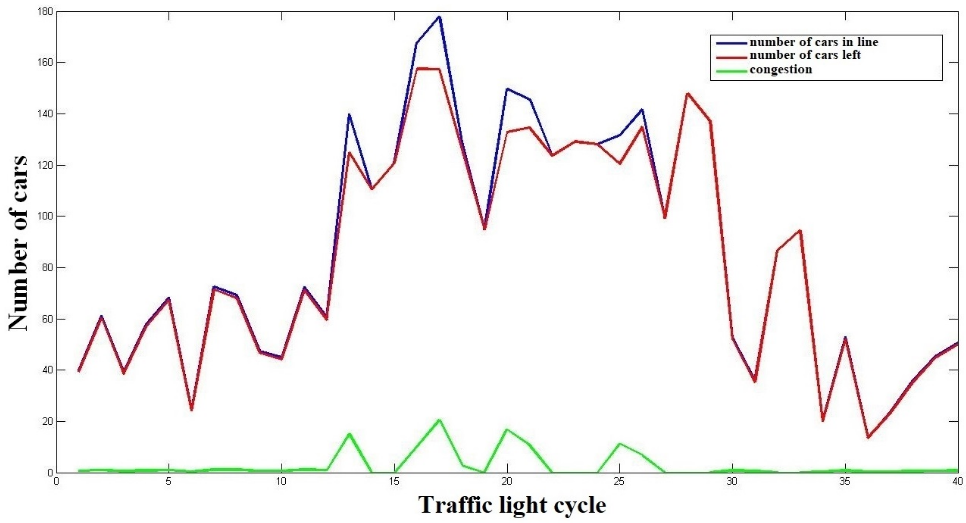

Figure 5: Improved fixed traffic light cd: Evolution of the numbers of cars on the ab(left) and cd(right): (blue-number of cars in line; red-number of cars left; green-number of cars that caught the second red light); Traffic light time: Green time in general: 55 s, Green time at rush hour 55 s, Red time: depends of the traffic light time ab.

In **Fig. 6** we represented the comparison between the number of cars in line at the red light if we use fixed and improved fixed traffic lights. As it can be seen, fixed-time traffic lights in general (red line with values up to 120 cars) are below the improved fixed (blue line values up to 180 cars), which means that the fixed time method was more efficient for cd. For this simulation on the ab direction the agglomeration was reduced by 33.71% using improved fixed traffic lights compared to the fixed method. The increase in green time for the ab increased by an average of 13.5 s during the red time (expected time in traffic) for the cd artery, which led to an increase of an average of 46 cars per cycle on this direction. The green area represents the surplus of cars that waited longer in the intersection (the difference between the red and the blue graph).

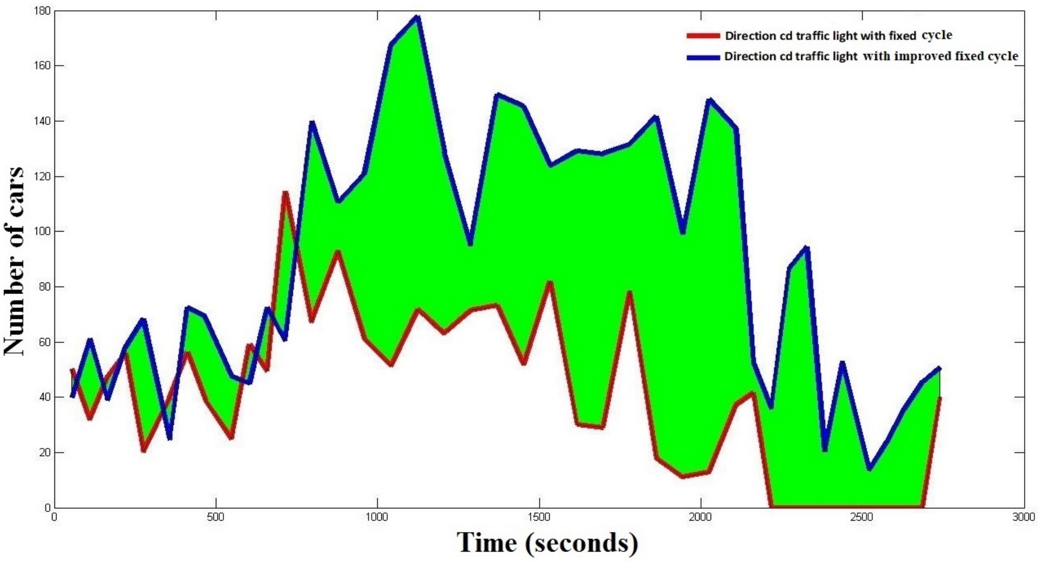

Figure 6: Comparison between fixed and improved fixed time traffic lights cd: blue - represents the number of cars waiting at the red light using improved fixed traffic light, red - represents the number of cars waiting at the red light using fixed traffic light, green area - the number of cars that would reduce traffic congestion.

Thus, the improved fixed method has fluidized only one direction of travel and therefore it is necessary a method that streamlines both directions.

4 Intelligent traffic lights

The Q-Learning (QL) algorithm is part of the Reinforcement Learning automated learning field and uses a Q table, consisting of states and actions, to find the best possible action to take in a given situation. The algorithm is based on increasing or decreasing the expected rewards for an actin undertaken in a given state. To optimize traffic, we used a modified QL algorithm, which considers two states (two important factors that lead to traffic congestion: state 1- the number of cars that remain on direction 1 after the green light and state 2 - the number of cars that accumulates on the 2nd direction at the red color) and inside the table there are the actions (traffic light times). The algorithm learns by successive repetitions and ends up building an optimal Q - see (1) - table of choices for a certain intersection. It has two steps: the calculation of the estimated passage time (if it has not already been calculated) and the updating of the values using the formula below based on the previous states and on the reward:

$$Q(S_t^1(i), S_t^2(j)) = Q(S_t^1(i), S_t^2(j)) + sign\left(\beta \cdot \frac{n_{last}(t-1)}{n_{last}(t-2)} + \gamma \cdot \frac{n_{acc}(t-1)}{n_{acc}(t-2)}\right) \quad (1)$$

where **n_last** is the number of cars left after the green color, **n_acc** is the number of cars accumulated at the red color and β, λ are reduction factors. The traffic light time (action) is chosen according to the current state. There is a continuous process of reward-based updating and the use of actions that have brought an optimum in the previous stages.

5 Urban network case study

In 2020, in the city of Bucharest, the congestion rate reached 42%, i.e. for a 30 minutes drive, the total duration would be 42 minutes [13]. We have chosen an intersection from Bucharest, located at Piata Unirii between IC Brătianu and Tineretului avenues. The traffic values we used are from a zonal control center and were obtained with inductive loops used for counting the number of vehicles. For the mentioned intersection, the ab direction is 6 times more crowded than the cd direction (see **Fig. 2**). For this intersection we made a comparison between the use of intelligent traffic lights using the QL algorithm detailed in the previous chapter compared to the fixed traffic lights currently used.

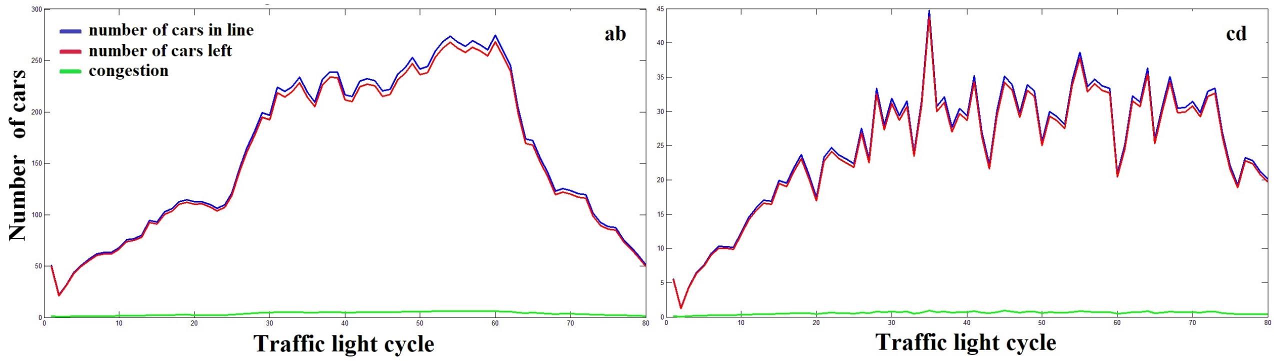

Figure 7: Intelligent traffic light ab and cd: Evolution of the numbers of cars on the ab-cd: (blue-number of cars in line; red-number of cars left; green-number of cars that caught the second red light difference between red and blue); Green and Red time in variable in range [20,75] s.

Following the intelligent variant simulation in **Fig. 7** (ab left), there is a very small difference between the blue and red graphs, i.e. almost all cars waiting at the traffic light leave in the same traffic light cycle without many cars left crowding the intersection (260 maximum value cars). In **Fig. 7** (cd right) it can be seen that the intelligent traffic light also fluidizes the traffic on the opposite direction, even if the number of cars is 6 times smaller than the ab. In both images in **Fig. 7** (ab and cd), at the intersection for the arteries ab and cd, the traffic is very well controlled using intelligent traffic lights based on variable traffic light times, and congestion is reduced. **Fig. 8** shows that the traffic light time for the green light is variable and depends on the analyzed traffic (we have short times for traffic below 150 cars in the ab direction and long times as the traffic reaches maximum values between 150 and 250 cars).

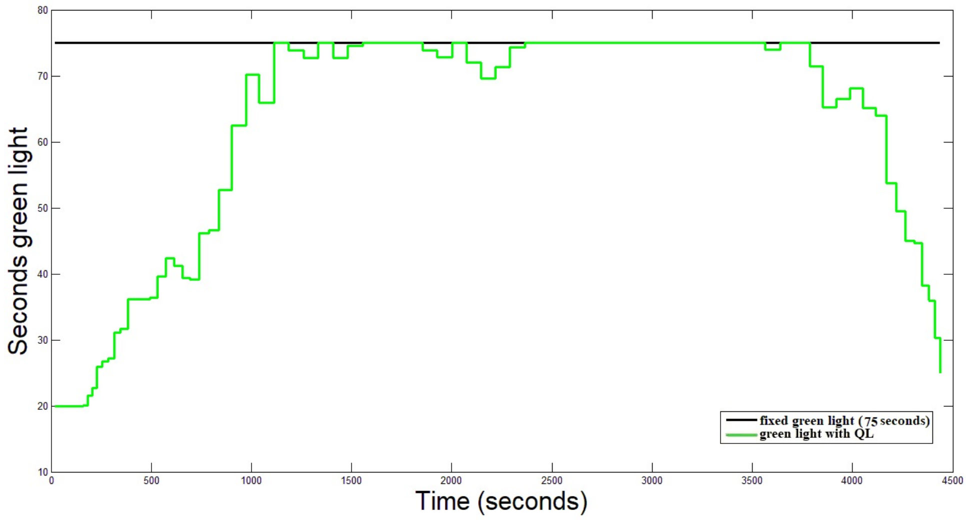

Figure 8: Variable green traffic light for artery ab in range [20, 75] seconds.

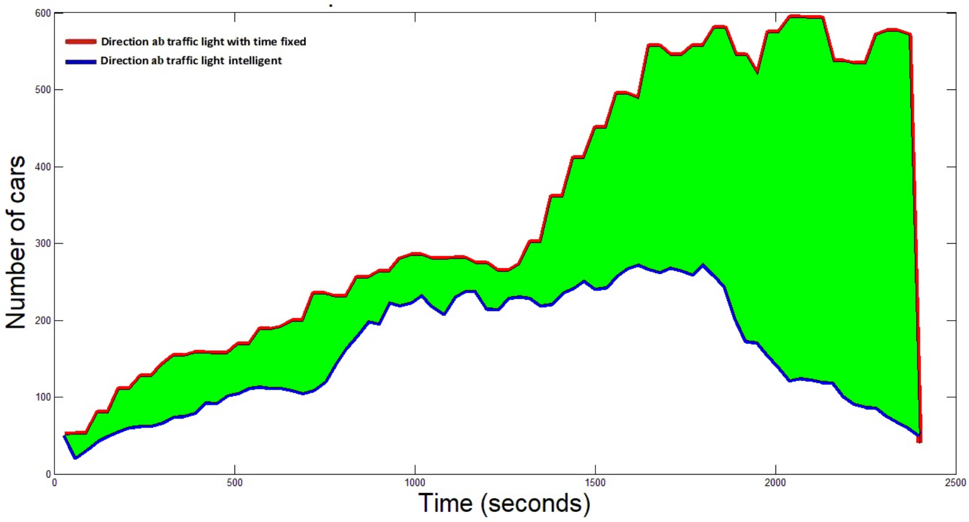

Figure 9: Comparison between fixed and variable time traffic lights ab: blue - represents the number of cars waiting at the red light using intelligent traffic light, red - represents the number of cars waiting at the red light using fixed traffic light, green area - the number of cars that would reduce congestion.

Fig. 9 shows in red the evolution over time of the number of cars for the version with fixed traffic lights, and in blue for the intelligent one. On the ab artery, which was the busiest in the Unirii area, the congestion decreased by 47% compared to the fixed one (green area). It is very clear that the intelligent method (blue line) is much more efficient than the fixed one. The same can be seen on the cd route. Here, too, the congestion dropped by 48%, even though the cd artery was not very crowded. In both figures the number of cars waiting in traffic is much lower for the traffic light with variable time (blue line) than the fixed one (red line).

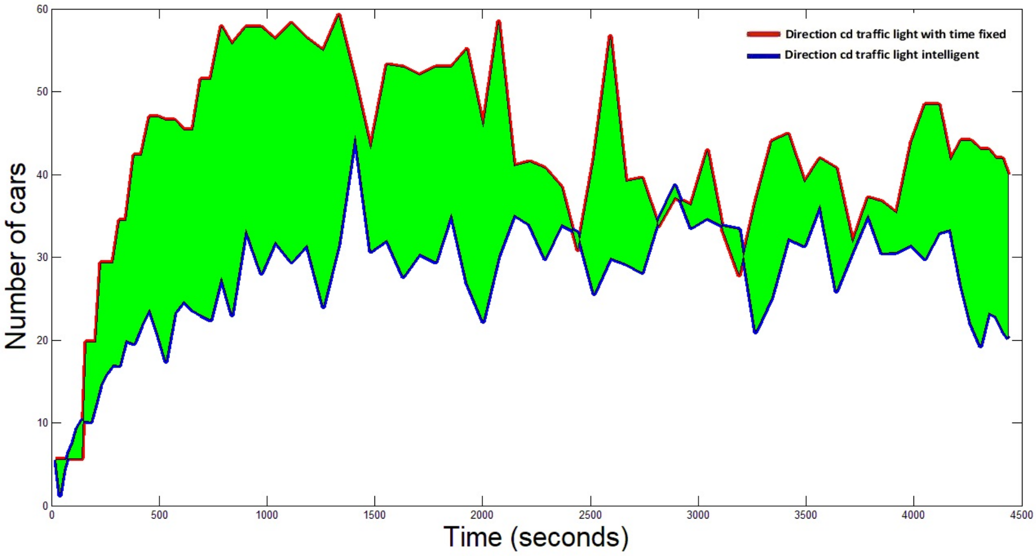

Figure 10: Comparison between fixed and variable time traffic lights cd: blue - represents the number of cars waiting at the red light using intelligent traffic light, red - represents the number of cars waiting at the red light using fixed traffic light, green area - the number of cars that would reduce congestion.

Table 1: Mean values for 40 cycles simulations, compared to fixed time traffic lights

Direction	Congestion reduction	Green time reduction	Red time reduction	Decrease in number of cars
a	47.32%	-	-	82
ab	51.95%	22.68 s	25 s	179
cd	48.40%	25 s	22.68 s	16
Intersection total	50.18%	47.68 s	47.68 s	194

At fixed time traffic lights there are moments (an example shown in **Fig. 10**) when a relatively large number of cars remain in traffic for a longer time than variable traffic lights and thus these cars will form congestion at each intersection. Overall, with the help of the QL intelligent traffic light, the congestion has been reduced by 50% compared to the fixed version, as can be noticed in the results detailed in **(Table 1)**.

6 Conclusions

The exponential increase in the number of vehicles in circulation and the existing limitations in road infrastructure are important concerns in modernizing traffic, especially in urban areas. The paper brings a solution to improve urban traffic by proposing an intelligent strategy for controlling and optimizing traffic light systems that act in real time with the flow of cars in traffic. The aim is to avoid congestion and assure traffic flow by controlling intersections in a heavily trafficked area.

The existing types of traffic light systems are analyzed, namely fixed and improved fixed traffic lights are compared in terms of variable traffic light cycles. Following, an automatic learning method (Q-Learning) is proposed. The QL algorithm works based on the weighting of the rewards used in relation to the states of the intersections given by the number of cars evaluated in real time.

The effectiveness of the proposed method for variable traffic light systems, supervised by the QL algorithm, was validated by simulation results, for data provided by an intersection in a crowded metropolitan area.

Future work will explore a practical application to transfer the theoretical and simulation results of our studies, toward a real traffic intersection.

Author contributions

The authors contributed equally to this work.

Conflict of interest

The authors declare no conflict of interest.

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Cite this paper as:

Dimon, C.; Teme, M.; Popescu, D. (2022). Optimization of Road Traffic Using Intelligent Traffic Light Systems, *International Journal of Computers Communications & Control*, 17(4), 4866, 2022.
https://doi.org/10.15837/ijccc.2022.4.4866