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A DYNAMIC TRAFFIC LIGHT MANAGEMENT SYSTEM BASED ON WIRELESS SENSOR NETWORKS FOR THE REDUCTION OF THE RED-LIGHT RUNNING PHENOMENON

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The real-time knowledge of information concerning traffic light junctions represents a valid solution to congestion problems with the main aim to reduce, as much as possible, accidents. The Red Light Running (RLR) is a behavioural phenomenon that occurs when the driver must to choose to cross (or not) the road when the traffic light changes from green to yellow. Most of the time the drivers cross even during transitions from yellow to red and, as a consequence, the possibility of accidents increases. This often occurs because the drivers wait too much in the traffic light queue as a consequence of the fact that the traffic light is not well balanced. In this paper we propose a technique that, based on information gathered through a wireless sensor network, dynamically processes green times in a traffic light of an isolated intersection. The main aim is to optimise the waiting time in the queue and, as a consequence, reduce the RLR phenomenon occurrence.

Keywords: Wireless Sensor Networks; RLR; Traffic Lights; Real-time; Intelligent Transportation Systems

1. Introduction

The number of vehicles constantly grows up both in small and large cities. One of the main goals of Intelligent Transportation Systems is to ensure road security, especially where there is the greatest number of accidents: traffic light junctions. Accidents at traffic lights occur for several reasons including the lack of care and the wrong management of traffic lights. Although many researchers focused on the study of innovative traffic lights management techniques, today most of the traffic lights are fixed cycles or manually controlled introducing human evaluation errors. These solutions can be adopted in road sections with low traffic flows. On the contrary, they produce several problems in areas with high vehicles density, such as the wrong green-time balancing, excessive fuel consumption and accidents caused by the Red Light Running phenomenon (RLR). The RLR phenomenon is a frequent and highly dangerous driving act. When a driver comes across a traffic light signal, changing from green to yellow, he must decide if accelerate or to brake according to his current speed and the distance to the stop signal. A wrong decision will lead him to a RLR violation or to an abrupt stop at the intersection. According to the authors of [1], [2] and [3], the proneness to RLR violations depends on two main factors, which influence the decision to stop or keep going at the intersection. These factors are as follows:

- human factor, related to population characteristics;
- road factors, related to traffic, geometric and operational characteristics of the intersection.

The technology can certainly play an important role in favour of these issues. Wireless sensor networks (WSNs) allow making different measures on the monitored traffic. Sensor nodes can be placed everywhere and provide several mechanisms to support energy savings [35]. They are also easy to deploy and manage. As a consequence, WSNs are particularly useful to monitor highly crowded roads. A distributed and clustered network infrastructure, for the real time evaluation of traffic flows, represents a concrete solution to the problem of road congestion monitoring. In this paper we present an experimental technique that allows the dynamic management of traffic light cycles using traffic flows information gathered through a WSN deployed near a traffic light junction. The main goal is to dynamically vary the green times based on the queue length, assigning then a greater green time to the road with the longest queue. In this way, by reducing the waiting times in the queue, it is possible to obtain a reduction of accidents caused by the RLR phenomenon. In most cases, accidents are caused by stress from excessive waiting times in queue. The paper is organized as follows. The Section 2 reports main literature works on road monitoring techniques using wireless sensor networks and on RLR. The Section 3 describes the proposed architecture. The Section 4 analyses the innovative and dynamic traffic lights management approach here proposed. The Section 5 shows performance evaluation of the proposed architecture while the Section 6 reports on the conclusions.

2. Related Works

2.1. Traffic lights management techniques using wireless sensor networks

Currently, most of traffic control systems use a wired communication infrastructure and this involves considerable maintenance costs reducing the architecture scalability. WSNs can be used [4] in order to solve these problems. In fact, an important application field of WSNs is road monitoring [5], as well as home automation [6], [7], health [8], agriculture [9] and industry [10], [11]. WSNs can be used for vehicular traffic detection in order to know real-time traffic information and help the drivers to make several decisions in order to optimise arrival time and to avoid queues. For these reasons, several works in literature deal with WSNs used for road traffic monitoring. In [12] the authors propose a compressing sensing technique which main aim is to reduce necessary communication among sensor nodes placed along the road. A solution based on a new network topology applied to sensor networks for road monitoring in order to improve performance in terms of throughput and energy savings is proposed in [13].

The authors of [14] propose a traffic flow segmentation technique based on the discrete Fourier transform using a data aggregation algorithm in order to minimize communication costs among the wireless sensor network nodes for urban traffic monitoring. The authors of [15] show a WSN application combined with video surveillance cameras. They describe novel network architecture in which surveillance cameras are dynamically enabled or disabled through a fuzzy logic controller based on information collected by sensors placed along the road. The aspect of queue management is discussed in [16]. In this work the authors describe a traffic scheduling mechanism through an algorithm for queues management called TRED (Traffic Random Early Detection). On the contrary, the Random Early Detection (RED) algorithm, the most common type of Active Queue Management (AQM) algorithms, is used in [17]. The authors propose an approach in which the road congestion is monitored based on the average queue length of vehicles and when a road is close to the congestion, the scheduler will forward the car on a different road. In literature several works show WSNs architectures for safety warnings signalling and for traffic lights management. In fact, in the approach proposed in [18], a WSN is used to automatically generate safety warnings at black spots along the road network. Instead, an architecture in which sensor nodes detect road information and send them to the nearest Intersection Control Agent, which determines the flow model of the intersection depending on data gathered by sensor nodes, is proposed in [19]. Moreover, the same authors propose in [20] results obtained using one sensor and two sensors. In both approaches, the obtained results show how to place the sensors close to each others produces the best performance in terms of quality of the data and reduces the energy consumption prolonging, as a consequence, the life time of the whole network. An intelligent traffic signals control system based on a WSN is shown in [21]. The authors propose an approach that uses the vehicle queue length during red cycle in order to perform a better control in the next green cycle. Their goal is to minimize the average waiting time in order to reduce the queues' length. In [22] and [23] the authors proposed an adaptive traffic light control algorithm that adjusts both the sequence and length of traffic lights in accordance with the real time traffic detected. The proposed algorithms consider several traffic factors (traffic volume, waiting time, vehicle density) in order to determine the optimal green light duration. The authors of [24] propose a fuzzy logic controller in order to dynamically adjust green time of traffic lights. According to the proposed approach, traffic flow can be detected by the single-axis magnetic sensors and transmitted through a wireless sensor network. The time for vehicles passing during the green lights is dynamically adjusted through the fuzzy algorithm according to the current volume of vehicles.

2.2. RLR analysis of road intersections

Some behavioural researches have clarified the role of the two different factors on RLR in terms of "dilemma zone" [25] and circumstances that make the red light running possible. In [26] it is suggested that in drivers' stop and go decisions, they should be considered the expectations due to previous knowledge of the intersection (especially waiting times at red lights), the assessment of the consequences of a violation and the estimation of the consequences of stopping. The study of [27] illustrates that the tree models are helpful to recognize and predict how the drivers make stop and go decisions and participate in red-light running violations, simply taking into account the traffic parameters. In urban areas, the optimisation of signal timings is really important to ensure the respect of traffic signals. The authors consider speed effects on RLR mostly associated with the human factor element. The FHWA (the Federal Highway Administration) recommends that signal timings must be regularly reviewed and updated (every 2 years) in order to ensure the satisfaction of current traffic demands. Indeed, the proper duration of each signal-cycle can reduce drivers' frustration that might result from unjustified short or long cycle lengths. The duration of each signal phase is based on the characteristics of the intersection and on the individual approaches. There are several philosophies and considerations, which support both shorter and longer cycle lengths in order to reduce signal violations. A driver, knowing that the waiting time is not excessive, may be less inclined to cross the road during the yellow or, even, during the red signal. On the contrary, in case of high traffic volumes, a short cycle length may not be enough to well manage all the queues and, as a consequence, the drivers may wait two or more cycles before to cross the road junction. Several previous researches, based on potential conflicts analysis, have provided a quantitative evaluation of 'proneness' to the red-light running behaviour at urban signalised intersections by varying geometric, traffic flow and driver characteristics. A recent study [28] demonstrated the potential of the use of micro-simulation models to evaluate the 'proneness' to RLR behaviour at urban signalised intersections in Milan (Italy), by varying flow characteristics and stop line distances. The micro-simulation, although at its early phase of development, is really promising especially for its ability to model unintentional RLR behaviour and to evaluate alternative junction designs. However, in order to make more robust the new modelling framework, the need to demonstrate the transferability of the modelling approach has been addressed in this paper [29]. The transferability has been tested and evaluated using a 4 arms junction in Enna (Italy), where has been realized a continuous video recording lasted 13 days. Moreover, in collaboration with the local Police, different cycle and green time's settings have been implemented in order to measure the effects on the RLR rates. Then, the measured RLR rates have been evaluated and compared to the theoretical and modelling results as validation exercise. In this way, the prediction capability of the proposed potential conflict model has been improved. The evaluation of the proneness to the RLR behaviour, as it results from human and road factors, can be useful to help a proper selection of the sites to be treated, thereby increasing benefit of the countermeasures to reduce the red-light running phenomenon. Starting from the conceptual framework of a model based on potential conflicts analysis, the authors of [30] show that a quantitative evaluation of the proneness to the red light running behaviour can be obtained both from the analysis of the effective operational characteristics of the intersection and from the actual number of red light running violations. According to the behavioural models referred in the literature, which emphasize the influence that both human and road factors have on the users' decisional process at red lights, the proposed approach also accounts for the impact of the local (site) and general (population) characteristics on the phenomenon. Field observations, for a case study in an urban area are discussed in order to illustrate the methodological approach. Some behavioural researches have clarified the role of the two different factors on the RLR decision. According to the authors of [26] in drivers' stop and go decision process three fundamental criteria are present:

- expectations and knowledge of intersection (especially regarding waiting times at red lights);
- estimation of the consequences of a violation;
- estimation of the consequences of a sudden stop.

From these considerations, it is possible to imagine a possible intentional RLR driver, impatient about a probable wait and not very worried about the risks of a violation. At the same way, it is possible to imagine the unintentional RLR driver that cannot suddenly brake or is approaching the intersection with insufficient attention. The authors of [31] observed that each user takes on a different role when is faced with the stop and go decision, depending on a given situation, on his/her mind set and on chance. In the light of this, four user categories can be distinguished, each characterized by a different inclination to infringe the red lights: reasonable and prudent; temporarily inattentive; reckless and mistaken driver. Although these studies qualitatively consider the influence of both human and road factors on the decisional process, they still do not provide any quantitative evaluation in terms of proneness to the red light violation. However, from an engineering standpoint, the qualitative data is unsatisfactory in order to establish appropriate countermeasures against the RLR phenomenon. Over the recent two decades, the RLR at signalised junctions has been well researched because of the human and financial costs to individuals and Governments due to accidents. Also, the effects of this phenomenon on road safety are well documented by several statistics [32], [31] highlighting both a very high frequency (up to an average value of 1 violation every 3.5 minutes) and the respective gravity of the consequences [33] with a growing intensity in recent years. In [32] a study of data from four States in the U.S. shows that RLR crashes account for 16% to 20% of the total crashes at urban signalised intersection. Evidence in [30] showed that about 5% of urban crashes are the result of red light runners.

3. System Architecture and Requirements

3.1. WSN System requirements

The knowledge of the real time situation of a certain road section is a fundamental condition for a better interpretation of the traffic flows. To achieve this goal, it is necessary to realize a monitoring environment based on different technologies in order to ensure the timely processing of information coming from the street. The Figure 1 shows the proposed system architecture.

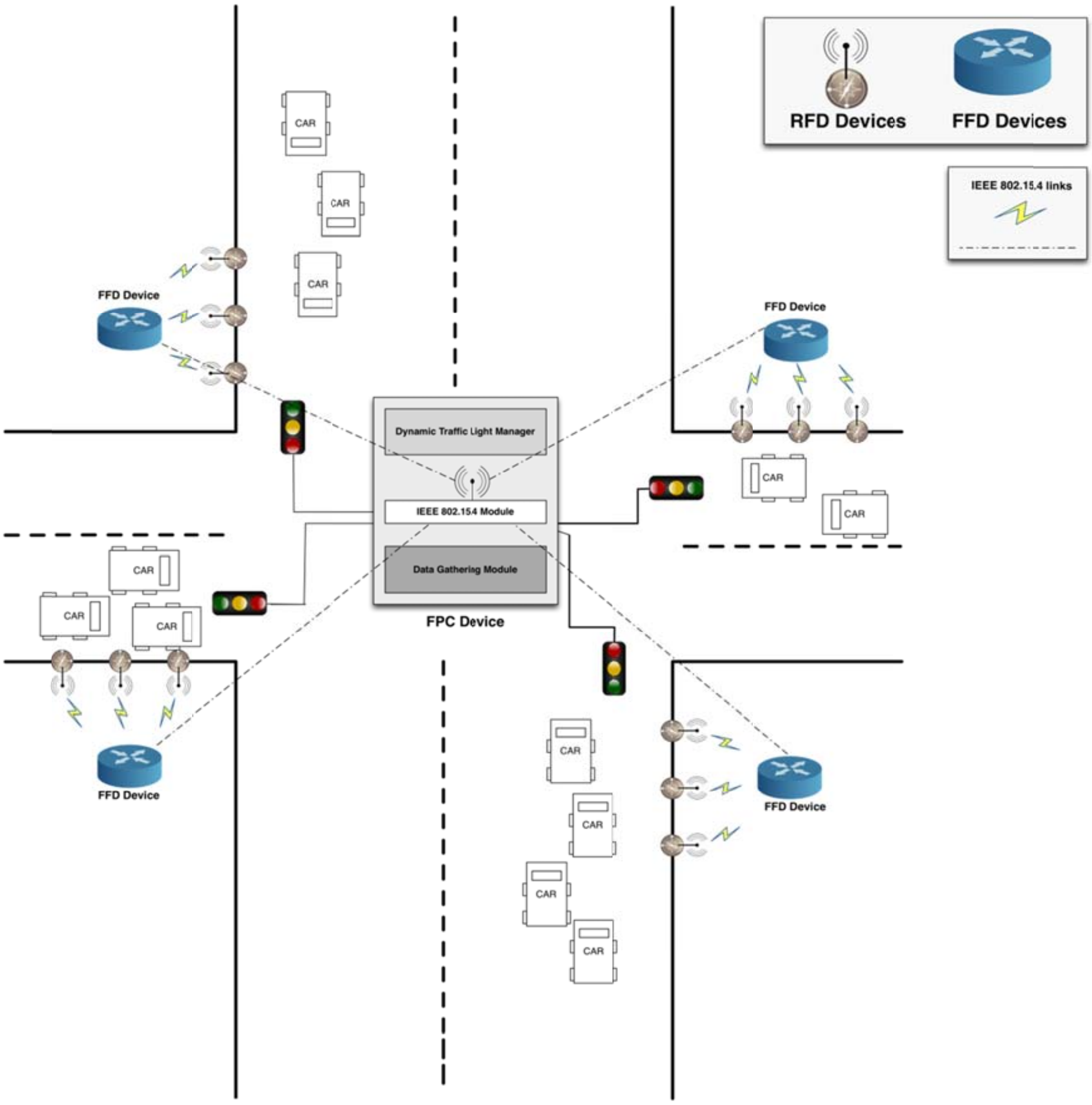

Figure 1. The system architecture

Road sections, near the traffic light junction, are monitored using appropriate nodes, Reduced Function Devices (RFD), provided with magnetic sensors in order to detect the presence of ferrous objects. The information gathered by the RFD is then forwarded to their relative Full Function Device (FFD), which collect information of their cluster and forward them to the First Pan Coordinator (FPC). As shown in Figure 1, the main modules provided by the FPC are as follows:

- a module for IEEE 802.15.4 [34] communication;
- a data gathering module;
- a dynamic traffic light manager characterized by an algorithm that, based on real time data detected by the network, determines the green times to be assigned to the road sections ensuring higher priority to longer queues.

The proposed system, as described above, can take over only the management of the traffic light and its optimisation. It can forecast the violations resulting from the traffic light variation but it cannot adjust the geometry of the intersection in order to prevent violations. The system, in other words, could lead to the base of knowledge about the violation rate, and in some case it highlights geometry deficiency in order to improve safety and reduce the RLR phenomenon.

3.2. Dynamic Traffic Light Manager

Considering the Figure 2, we indicate with R_A the road section containing traffic lights 2 and 4 and R_B the road containing traffic lights 1 and 3.

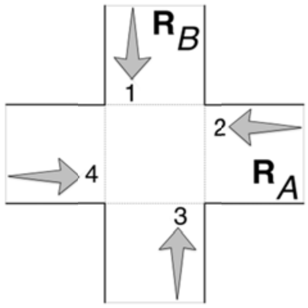

Figure 2. Road intersection

In static traffic lights, each cycle can be approximated to a periodic task with period **T** divided in a fixed green time (**T**$_g$), a fixed yellow time (**T**$_y$) and a fixed red time (**T**$_Y$). Of course, under these conditions, each road section queue will be handled in the same way regardless of its length and not considering the dynamic behaviour of the queue. Our goal is to realize a mechanism in order to dynamically determine the traffic light cycles based on vehicles number in queue. The Figure 3 shows a road section of length $\boldsymbol{L}$ subdivided into smaller sub-sections, each one of length $\boldsymbol{l_i}$.

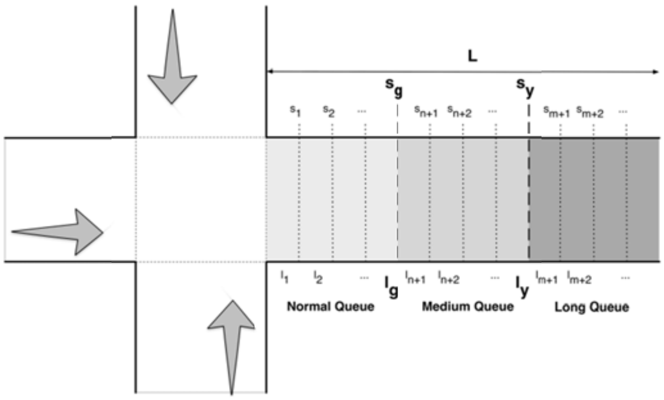

Figure 3. Monitored road section by wireless sensor networks

Each subsection $\boldsymbol{l_i}$ is monitored by a node in order to detect the presence of vehicles through a magnetic sensor [35]. Each node communicates with other nodes and the FPC according to the IEEE 802.15.4 [34] standard protocol. The algorithm evaluates the traffic light cycles considering three fundamental parameters: the road section length (*L*) to be monitored; the sub-sections length ($\boldsymbol{l_i}$); the approximate crossing speed ($\boldsymbol{v}$). Most of vehicles, waiting at the traffic lights, are cars. The average length of a car is between 3.5 and 5 meters. Considering that vehicles may be shorter or longer, the length of each subsection ($\boldsymbol{l_i}$) can assume values between 4 and 8 meters. We decided to places the RFD nodes every 12 meters while the FFD nodes every 60 meters. Finally, the FPC can be placed at the end of the road near the traffic light. In a small city, the average speed ($\boldsymbol{v}$) of a vehicle crossing a traffic light intersection is 15 Km/h. Let consider $\boldsymbol{l_g}$ the maximum value within which a traffic light queue is considered normal while l_y is the maximum value within which the queue can be considered medium. Above this value, the queue is considered long. The number of subsections is calculated as L/l_i while the l_g value can be determined by the following relation (1):

$$l_g = \frac{\left(\frac{L}{l_i}\right)}{3} + 1 \quad . \tag{1}$$

The number 3 at denominator represents the number of categories into which the queue has been divided (normal, medium and long) while the 1 represents a guard value arbitrarily chosen.

The l_y value, therefore, is calculated through equation (2):

$$l_y = \left(\frac{L}{l_i}\right) - 1_g \quad . \tag{2}$$

In case of vehicles detection in a section $l_i < l_g$ the traffic light works under standard conditions. In case of vehicles detection, in a section $l_g < l_i < l_y$, the estimated queue length is considered medium. Instead, $l_i > l_y$ is the condition of long queue. The crossing time of a single subsection can be easily estimated through the following equation (3):

$$t_i = \frac{l_i}{v} \quad , \tag{3}$$

where l_i represents the i-th section length while v is the approximate crossing speed of the relative road section. In case of medium or long queue, the green time must be recalculated according to the estimated queue length.

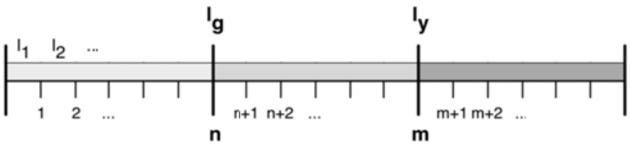

Figure 4. Sections subdivision

Considering the subdivision of the sub-sections shown on Figure 4, the standard green time t_g and the real-time green time t_{grt} can be calculated through the following relations (4):

$$\begin{cases} t_g & if\ l_i \le l_g \\ t_{grt} = t_g + \dfrac{l_j + l}{v} & if\ l_g < l_j \le l_y\ with\ j = n+1, n+2, \dots, m \\ t_{grt} = t_g + \dfrac{l_k + l}{v} & if\ l_k > l_y\ with\ k = m+1, m+2, \dots \end{cases} . \tag{4}$$

The terms $(l_k + l)/v$ and $(l_j + l)/v$ represent each one ratios between space and speed. In other words, they represent values of time to be added to the standard green time t_g in case of increasing queue in order to slightly increase the total green time and to allow the real-time management of the traffic light according to the queue behaviour. Clearly, the road that has the longest green time has higher priority. Each traffic light independently calculates, during each period, its green time in order to determine its priority level according to the following relations (5):

$$\begin{array}{lll} p_i = t_g & if\ l_i < l_g & with\ i = 1,2,3,4 \\ p_i = t_{grt} & if\ l_i > l_g & with\ i = 1,2,3,4\ , \end{array} \tag{5}$$

where p_i is the priority of the *i-th* traffic light. At the end of the period T_i, the algorithm determines the road with highest priority determining which traffic light needs more green time. The priority of each road is calculated through equation (6) and (7), as the average of the individual priorities calculated by each traffic light adding a Δ value (that can be positive or negative). This Δ value is then divided by two in order to avoid that the priority, acquired by a road, can be too high (excessive green times).

$$P_{R_A} = \frac{(p_1 + p_3)}{2} + \frac{\Delta_A}{2} \quad , \tag{6}$$

$$P_{R_B} = \frac{(p_2 + p_4)}{2} + \frac{\Delta_B}{2} \quad . \tag{7}$$

4. Performance Evaluation

4.1. Traffic lights manager evaluation

The simulations have been carried out both in case of fixed and dynamic traffic light cycle in order to demonstrate the goodness of the proposed approach. Performance have been evaluated considering a 4-arms junction placed in Enna-Italy, where up to 160 vehicles can be measured on each road. In both cases, the reference cycle was 60 seconds and measurements have been gathered for 60 cycles (1 hour). The length of each road approaching the traffic light junction is 1.5 Km. For completeness, durations of fixed traffic light cycles are: minimum duration: 30"; normal duration: 50"– 75"; maximum duration: 90"– 120". The Figure 5 shows the number of vehicles measured and smoothed in Road A in case of Fixed Cycle (left side) and Dynamic Cycle (right side) respectively. As it is possible to see, in case of fixed cycle, the queue it is not correctly managed. In fact, on average 23.08 vehicles/minute are measured near the traffic light but, of these, just 11.33 vehicle/minute are smoothed (about 49 %). On the contrary, in case of dynamic cycle, 21.083 vehicles/minute are smoothed (about 91 % of the total number of vehicles transited).

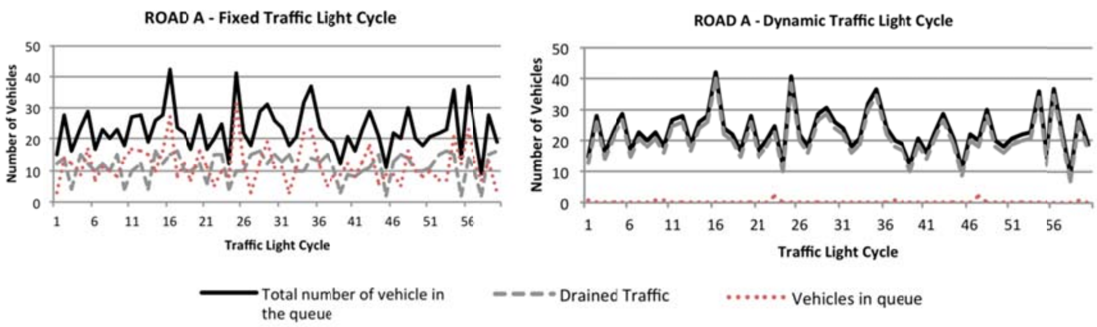

Figure 5. Road A – measures obtained with fixed and dynamic Traffic Light

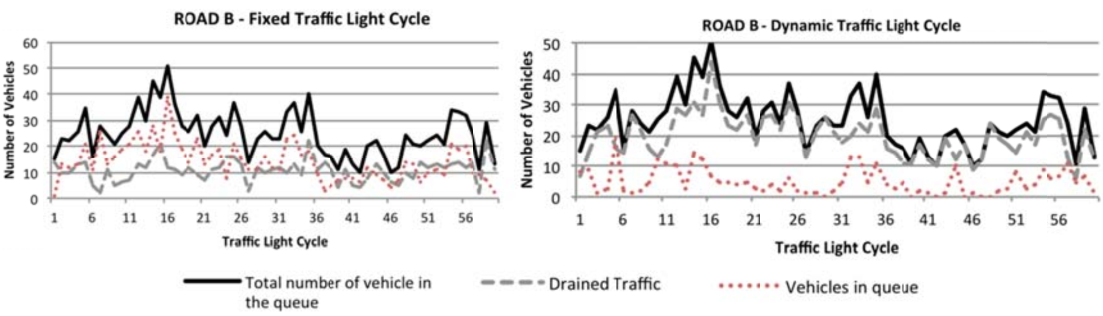

Figure 6. Road B – measures obtained with fixed and dynamic Traffic Light

The Figure 6 shows measurements carried out along the road B in case of "fixed-cycle" traffic light (left side) and dynamic traffic light (right side). In the first case, on average 24.95 vehicles/minute have been detected. Of these, just 10.81 have been smoothed (about 43.35 %). Otherwise, considering a dynamic traffic light that uses our approach, 19.93 vehicles/minute have been smoothed (about 80 % respect to the total number of vehicles transited).

4.2. Evaluation of driver behaviour in Italian signalised intersections

The intersection number and several human factors influence the RLR phenomenon. It is important to examine how these factors interact to increase or decrease the RLR risk in order to identify the several reasons of RLR occurrences. The Red Light Runners can be categorized into intentional and unintentional violators. In general, appropriate countermeasures should help to manage them.

Excluding users who did not use drugs and alcohol, the main factors that lead to the occurrence of RLR can be divided as follows:

- Drivers characteristics: gender, age and type of driven vehicle (heavy or light);
- traffic-light characteristics: cycle and change of phases;
- intersection characteristics: geometry, triangles of visibility, presence and analysis of the black spot, different types of construction presence that can adversely affect the driver and therefore distract him from driving manoeuvres;
- when the phenomenon occurs: evaluation of the peak traffic flow considering every different moment of the day such as morning, afternoon or evening.

Considering the yellow phases in the traffic-light cycle, in several states there are two types of restrictive laws described below:

- vehicles can not enter the intersection or be in the intersection during red light;
- vehicles must stop upon receiving the yellow light indication, unless it is not possible to do it safely.

These factors need to be considered in combination with the intersection definition when developing a plan in order to manage the RLR phenomenon. Public information and education campaigns would be needed in order to have an exhaustive knowledge regarding to the meaning of the yellow indication. Another characteristic refers to the demographics category that includes the age, the gender and the vehicle occupancy. It is also important to consider whether or not the red-light runner was wearing a seat belt. In fact, younger drivers, between 18 to 25 years old, are more likely to run on red lights compared to older drivers. Moreover, the majority of red-light runners are males and are less likely to wear safety belts. Specifically, the drivers run on red lights when they drive alone or have an older car.

Regarding to the driving speed, the drivers may:

- accelerate during yellow in order to anticipate a signal indication change. If a driver misjudges the time of signal change, he will enter the intersection against the red signal indication;
- to drive above the speed limit, decreasing the available distance to react to a traffic signal indication change.

The drivers who closely follow another vehicle are more likely to run a red light. Taking into consideration the different types of vehicles transiting, it is statistically significant that there are differences between RLR rates if a driver follows a smaller or a larger vehicle. In fact, there are higher rates of RLR if a driver drives behind a larger vehicle due to the visibility. Moreover, the traffic volume is an important factor of direct increase of the RLR phenomenon. In order to fit the problems related to the traffic-light cycle and the RLR phenomenon, the Figure 7 shows the correlations obtained in regarding the number of violations related to traffic light cycles on main and secondary direction.

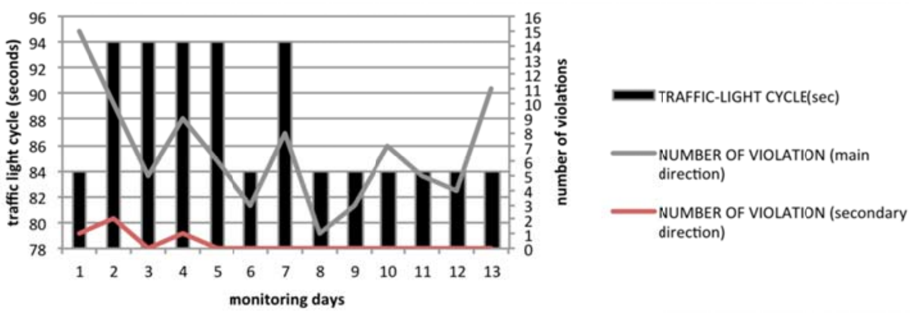

Figure 7. Trend of violations according to the traffic-light cycle about a typical 4-arm signalised intersection

Furthermore, the study shows a correlation between the frequency of the signal variations and the current red light. If the time cycle increases, the hourly frequency variations of the signal decrease reducing, as a consequence, the exposure of drivers to potential red light situations. The presence of a wireless sensor network that detects the possible transgression and dynamically adapts the traffic-light cycle, leads to a reduction of the RLR phenomenon occurrences. Recognizing the importance of this issue, it's possible to consider the studies of University of Florida (Transportation Research Centre) where some researchers started a program to develop the necessary hardware and software to support field studies in efficient and effective way. The central element of the system for collecting data from the American University is a red light Analysis Package (RLRAP) which provides the enabling technology to observe vehicles in violation of a red signal superimposing the state of all traffic signals on a video image of the complete intersection. Through the implementation of wireless sensors therefore, in agreement with what has been said, it is possible to see all vehicles and all signals simultaneously.

5. Conclusions

Increasing traffic volumes and congestion in many urban areas, determine drivers impatience and frustration. Sometimes these conditions lead to an aggressive drivers' behaviour and disregard for road laws and signals. These violations, including the RLR phenomenon, decrease the safety of drivers and pedestrians. In this paper we proposed a novel technique for the dynamic management of traffic light cycles in order to reduce the queues in road sections and, as a consequence, accidents due to the RLR phenomenon. To this end, a wireless sensor network has been implemented with the aim to gather real time information about roads' congestion. These information are then processed by a central node (the First Pan Coordinator) equipped with a special module that, based on a novel algorithm, dynamically processes the traffic light cycles reducing, at the same time, waiting times and drivers frustration. The results shown, clearly demonstrate how the proposed algorithm improves the queue management near a traffic light.

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