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Intelligent traffic signals: Pivotal innovations for sustainable urban traffic management

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Abstract. As living standards rise, there is a noticeable surge in the number of private vehicles. This increase places considerable strain on urban transportation, leading to significant congestion in metropolitan areas. This research delves into the establishment of intelligent traffic control, focusing specifically on the signal light control system to address this growing concern. The realm of intelligent transportation seeks to bolster the efficiency, safety, and environmental sustainability of transit systems. To discern variations and identify potential bottlenecks in traffic flow, the background difference method compares traffic data over distinct time frames. This paper melds the background difference method with the SORT tracking algorithm to meticulously recognize and monitor vehicles. Two timing algorithms, Webster and ARRB, are explored in this study. Both are commonly employed to optimize traffic signal control and amplify the fluidity of traffic movement. Presently, the domain of intelligent transport systems is transitioning to embrace digital advancements, aiming to offer astute, efficient, and user-friendly traffic management solutions.

Keywords: Intelligent Transport, Background Differencing, Webster, Digital.

1. Introduction

Efficiency within urban transportation operations acts as a crucial benchmark for evaluating a city's advancement in management and governance capabilities [1]. Nonetheless, hands-on observations pinpoint a pressing challenge during peak travel times. During these periods, urban gridlocks often escalate to severe degrees, occasionally making the pace of motor vehicles lag behind even bicycles. The core issue propelling this scenario forward is the insufficiency of prevailing traffic signal control strategies [2].

Presently, a significant portion of global cities employs a control system rooted in set timings. Such a mechanism lacks the capability to fine-tune in real-time based on evolving traffic conditions at crossroads. This shortfall stems from the system's foundation on historical traffic patterns and the tangible expertise of traffic officers. Consequently, scholarly endeavors are gravitating towards the innovation of astute traffic signal control systems that can adaptively resonate with immediate vehicular data on roads. The exploration of intelligent traffic signal control systems, given their potential to alleviate urban traffic snarls and augment the governance proficiency of city administrations, has ignited considerable academic interest [3]. In this manuscript, the focus zeroes in on methods to perpetually oversee traffic scenarios at intersections and to dynamically recalibrate signal durations grounded in

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such insights. Such adaptations pave the way for diminishing traffic bottlenecks and uplifting the overarching efficacy of transportation flow.

2. History and Evolution of Intelligent Traffic Signals

2.1. The Genesis of Conventional Traffic Signals

Traditional traffic lights have their roots in prehistoric civilizations, according to historians. The first traffic signals were manual hand signals and aural signals that were used to control traffic and guarantee a smooth flow of it. Flags and yells were utilized by ancient civilizations, particularly Roman towns, to control traffic. As urban traffic expanded, these hand and sound signals became more significant [4].

2.2. Rise and Progression of Intelligent Traffic Signals

This study uses the history of ITS development in the US as an illustration. In the United States, ITS (Intelligent Transportation Systems) underwent a start-up phase during the 1960s and 1980s, with a large emphasis on issue identification and requirement research. Much early research has been done since the 1960s, even if the systematic development of ITS only started in the 1990s [5]. In order to solve difficulties with traffic congestion and safety, an intense drive for infrastructure, such as interstate roads, was launched around 1940 as a result of a dramatic increase in the number of motor vehicles in the United States. This prompted the investigation of efficient traffic control strategies independent of infrastructure. The U.S. government started looking into systems like the Driver Aid Information and Routing (DAIR) system and the Electronic Route Guidance System (ERGS) in the late 1960s. These systems were intended to give drivers travel information services, including in-vehicle displays, equipment for monitoring the road, and communications. The first ITS applications emerged in the 1980s as a result of the government, business, and academics recognizing the promise of new transportation technology. With the practical application of navigation technology, electronic toll collection systems, and other forms of traffic management, the development of ITS in the U.S. entered an early stage in the 1990s and late 1990s, with the primary goal of improving the operation of the transportation system. In order to make up for the absence of policy, the U.S. also started to create rules and regulations at the same time [6]. The ITS project received significant financial assistance from the ISTEA (Intermodal Surface Transportation Efficiency Act) in 1991, which also set forth the objective of utilizing cutting-edge technology to improve traffic efficiency and safety. In order to address deficiencies in policy, the United States also started to create laws and regulations at the same time. The Intermodal Surface Transportation Efficiency Act (ISTEA), approved by the US Congress in 1991, laid forth the objective of utilizing cutting-edge technology to improve traffic safety and transportation efficiency while also providing significant financial assistance for ITS projects. The ITS Joint Project Office, founded by the Department of Transportation (DOT) in 1994, provided the basic structure for the ITS system in eight domains, including electronic payments, driver and traveler services, emergency response, and public transportation operations, among others [7]. The National ITS System Architecture, which outlines the user services and needs, logical structure, and physical structure of ITS in the United States, was completed by the United States in 1996.

2.3. International Case Study

At the moment, numerous methods and algorithms are continually being developed to enhance traffic control systems. Results of international research are available:

Using infrastructure for reverse traffic, Sihua Shao and Abdallah Khreishah from the United States presented an intelligent system for vehicle location in 2020. The device employs a Dual-PD receiver mounted on the car's headlights to gather information from modulated reflected signals. This modulated light signal may be used to position the vehicle horizontally inside the lane by distinguishing it from reflected signals from objects on the road. The technology can optimize travel in real time by interacting with other cars [8].

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A congestion-based traffic forecast model was created in 2021 by Attila M. Nagy and Vilmos Simon of Hungary, and it increased the model's accuracy by 9.47% in comparison to earlier traffic flow prediction methods [9].

Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies are used in ITS in European nations to increase traffic safety. The sophistication of electric automobiles and public transportation networks is being promoted in Europe.

A larger variety of data kinds may be detected using video monitoring. To identify the best timing solutions, deep reinforcement learning extracts more hidden characteristics and engages with the environment [10]. Therefore, integrating deep reinforcement learning with video surveillance for intersection signal control methods has a bright future.

3. Core Technologies Behind Intelligent Traffic Signals

3.1. Image Acquisition and Data Processing at Traffic Intersections

Bitmaps are a particular kind of digital picture having the following features: 1. A bitmap is a type of digital picture that is made up of pixels, each of which has a specific color value and can thus generate vibrant colors. 2. Bitmaps have a strong expressive capability that allows them to depict visual subtleties and details in high resolution and true colors. Table1 displays common categories and traits.

Table 1. Bitmap Image Categories.

Bitmap Image Categories	Traits
RGB images	This kind of bitmap, which is a typical sort of color picture, represents color using a mixture of the primary colors red, green, and blue. It consumes a significant amount of memory.
Binary image	When representing binary information in an image, such as text or shape borders, binary bitmaps, which typically only have two colors—often black and white—are utilized. The quantity of memory and data processing used is similarly minimal.
Greyscale image	The use of varying grey levels to express color depth, often between black and white, is appropriate for many image processing applications such as picture enhancement and analysis.

The system designed in this paper uses grey scale images converted from RGB images. This simplifies the image information, saves storage space and accelerates image processing.

The commonly used algorithms for motion target detection are frame difference method and background difference method. The frame difference method is small in computation and adaptable, but it can only extract the boundary of the image and cannot detect the stationary image. The signal light control system requires real-time, so this paper chooses the background difference method as the detection algorithm. The principle is shown in Figure 1.

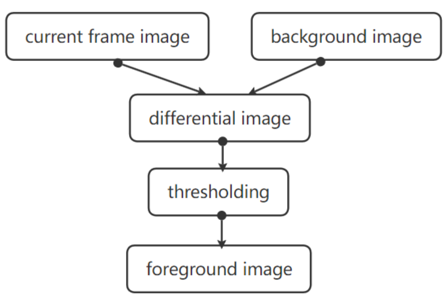


Figure 1. Background difference method (Photo/Picture credit: Original).

The main objective of image preprocessing is to eliminate useless information from the image. To achieve this goal, preprocessing consists of the following steps:

Step 1: Grayscaling The target image captured by the video detector is usually an RGB image. However, RGB images are not suitable for meeting the real-time requirements of traffic signal control due to their high memory footprint and arithmetic complexity. Therefore, the first step is to convert the colour image into a greyscale image. This can be done in greyscale by equation (1).

$$Gray = 0.999 * R + 0.587 * G + 0.144 * B \tag{1}$$

Wherein, Gray denotes the grey value of the grey scale image. R, G, B denote the red, green and blue luminance values of the colour image respectively.

Step 2: Background Differencing.S

Video image processing requires real-time updating of the background, which is separated from the foreground using the Mixture of Gaussian Models (MOG) algorithm. MOG represents the background and foreground in an image as separate Gaussian distribution functions, and matches the pixel points of consecutive frames by building a Gaussian model to obtain the target image. Instead of processing in the initial background, this method builds on the previous frame of the image to adapt to dynamic environmental changes. The MOG algorithm is a better performing background modelling method.

Step 3: Binarisation.

Binarisation is the computational conversion of an image with 256 different colour depths between 0 and 255 into an image that displays only two grey values, 0 and 1. This processing causes the image to display only black and white colours.

$$S_i(x, y) = \begin{cases} 0, S_i(x, y) \le T \\ 1, S_i(x, y) > T \end{cases} \tag{2}$$

$S_i(x, y)$ denotes the grey scale value and T is the set threshold.

Step 4: Filtering and denoising

While filtering aims at suppressing image noise and preserving details, denoising aims at removing interfering information in order to obtain critical information in the image.

3.2. *Intelligent Decision-Making Algorithms*

In order for the signal timing algorithm to make the optimal signal light regulation strategy according to the real-time traffic state, it is necessary to obtain the relevant characteristic parameters that can characterize the real-time traffic state. The video images captured by the video monitoring are processed to obtain the license plate information, traffic flow and calculate the length of the vehicle queue.

3.2.1. License plate extraction technology is the basis for realizing intelligent traffic. The license plate recognition process is shown in Figure 2.

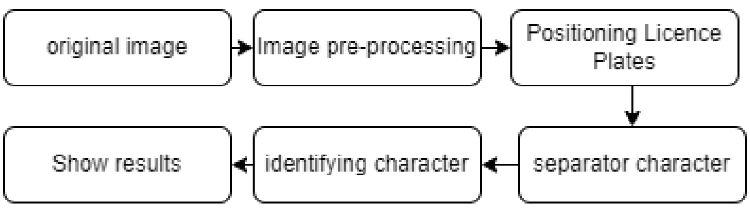


Figure 2. Vehicle license plate recognition (Photo/Picture credit: Original).

3.2.2. Target tracking. The core steps of SORT target tracking algorithm are: target detection, Kalman filtering to predict the state, Hungarian algorithm to match the target, and Kalman filtering to update the state. Among them, Kalman filtering algorithm mainly predicts and updates 8 feature vectors of the detected target. The Hungarian algorithm constructs the similarity matrix through the size of the

Intersection over Union (IOU) between the target frames of the two frames before and after, so that the two frames before and after match the correct target. The algorithm effect is closely related to the performance of the detector, so it is necessary to combine an excellent target detector with the tracking algorithm. In this paper, its combine the background difference method and SORT algorithm to track vehicles at intersections.

3.2.3. Traffic flow detection. Continuous position information can be obtained through the target tracking algorithm, so that the traffic flow can be detected. The flow of traffic counting is shown in Figure 3.

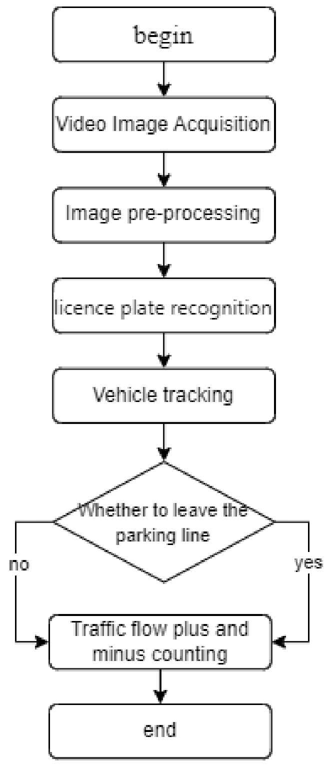


Figure 3. Flow counting process (Photo/Picture credit: Original).

3.2.4. Vehicle queue length detection. Step1: Initialise the parking markers in each lane to False;

Step2: read video one frame image;

Step3: determine whether a parking event occurs in each lane. If a parking event occurs, set the parking marker of the corresponding lane to True and record the time stamp of the parking event. If it has been marked as a parking state and no parking event is detected again after a period of time, reset the parking marker to False

Step4: If the parking marker for the current lane is True, perform the next step, otherwise skip the queue length detection for that lane.

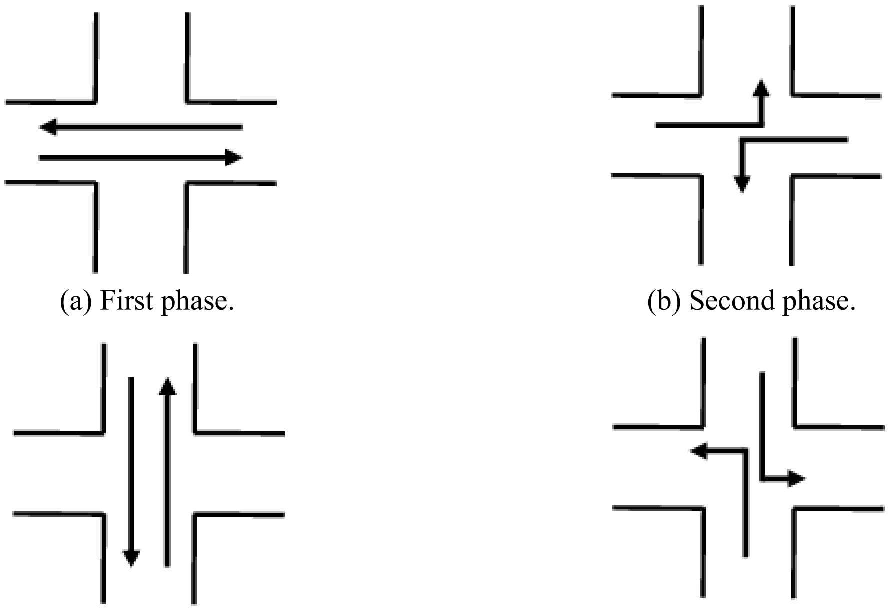
Step5: Record the position information of all targets in that lane and vertically project the top-left vertex of the target box onto the queue detection line of that lane

Step6: Sort all targets according to the distance from the starting position of the queue length detection line.

Step7: Starting from the starting point of the queue detection line, calculate the Euclidean distance between two adjacent targets on the detection line one by one. If the distance is less than a threshold that changes adaptively according to the target position, the near-end vehicles are included in the convoy until the non-compliant targets are found. At this time, the Euclidean distance between the farthest target in the convoy and the start of the detection line is used as the queue length.

Step8: After completing the detection of all vehicle targets in the current frame image, go back to Step 2 and continue processing the next frame Figure 3 Communication Systems and Hardware Blueprint.

3.2.5. Traffic Light Timing Algorithm. In this paper, we focus on the intersection of a four-phase schematic of a typical conflict-free region (shown in Figure 4). There are many forms of phase settings, but this paper is concerned with the four-phase and conflict-free case.



(a) First phase. (b) Second phase.

(c) Third phase. (d) Fourth phase.

Figure 4. Phase type (Photo/Picture credit: Original).

Currently, the most common classical traffic timing strategies include the Webster traffic timing algorithm proposed by Professor Webster and the ARRB traffic timing algorithm proposed by Professor Akcelick.

Webster Timing Method.

By calculation, the optimal timing is.

$$C = \frac{1.5L + 5}{1 - Y} \tag{3}$$

$$Y = \sum_{i=1}^{n} \max(y_{i1}, \cdots y_{im}, \cdots) \tag{4}$$

Where C denotes the cycle optimal duration; L denotes the traffic loss time in s; n denotes the total number of phases; Y denotes the sum of the maximum flow ratios; and y_{im} denotes the flow ratio of m lanes in the i-th phase.

(2) ARRB traffic timing algorithm.

The algorithm gives the stopping compensation factor to adjust the minimum delay time and minimum number of stops. The formulas are as follows

$$PI = L + KH \tag{5}$$

L, K, and H represent the following concepts: total vehicle delay, stopping correction factor, and total number of vehicle stops at the intersection, respectively.

When the PI is minimum, thus deriving the optimal signal period as $C_0 = \frac{(1.4+K)L+6}{1-Y}$.

It is worth noting that both algorithms are only applicable when the saturation level is less than 1. When the road saturation is greater than 1, the algorithms increase road congestion.

3.3. Communication Systems and Hardware Blueprint

Digital transformation is the future development trend of ITS, whose characteristics include the continuous evolution of digitalization, networking and intelligence.

For data processing, with the help of existing cloud computing technology, a cloud control platform can be constructed to unite a large number of high-speed computers spread all over the world into a huge virtual resource pool through the network to provide computation and storage services for distant Internet users, thus reducing the hardware and software cost of ITS and improving the computation efficiency.

In terms of data storage, due to the diversity, wide range of sources and long-term storage needs of traffic big data, since the construction of ITS has entered an accelerated phase, the development of cloud computing technology has provided a new solution to the big data storage problem. The pressure of data storage can be eased through the virtual resource pool integrated in the cloud.

As far as data transmission is concerned, at present, urban ITS mainly adopts the combination of autonomously constructed transport private network and urban public network, with gateways for data filtering set up between the private network and the public network, and both wired and wireless communication methods are used. Wireless transmission usually uses GPRS and ZigBee technology to transmit data, using the TCP/IP network protocol for GPRS network connection management, adopting a transparent transmission method, and combining the TCP protocol to achieve a reliable connection between the controller and the server. ZigBee technology, on the other hand, is a kind of low-power and low-cost bidirectional wireless communication technology, which belongs to the local area network (LAN) protocol, and is very suitable for the urban traffic signal light system.

4. Challenges

- ITS must comply with a variety of regulations and standards, including traffic regulations, data privacy laws, etc. Ensuring compliance can pose challenges. ITS involves the collection and processing of a large amount of sensitive data, and how to ensure data security and privacy protection is a key challenge
- In this paper, only the impact of motor vehicles is considered. However, the traffic situation in real life is more complex, and the actual traffic structure consists of pedestrians, non-motorized vehicles and motorized vehicles. At the same time some special vehicle behaviour also needs to be considered
- Only one means of data monitoring will lead to insufficient anti-interference ability of the system. It is easily affected by environmental changes such as late night or extreme weather.

5. Conclusion

This study employs a video image capture methodology to record junction traffic in real time. Through advanced target tracking and image processing techniques, parameters such as vehicle queue length are ascertained. The Webster and ARRB timing algorithm is then applied to establish the optimal interval duration for traffic signals based on these derived metrics. Cutting-edge technology facilitates the analysis of the progress in digitalizing Intelligent Transportation Systems. It is anticipated that future iterations of the traffic signal management system will incorporate the impact of pedestrians, non-motorized vehicles, and specialized vehicles on road conditions. There is also an aspiration to enhance traffic coordination by establishing a link between traffic signal systems and individual automobiles. With real-time signal information sourced from communication channels between vehicles and the traffic light infrastructure, drivers can make better-informed decisions during their journeys. Furthermore, to fine-tune the signal timing with greater precision, upcoming traffic light systems are expected to predict traffic patterns and congestion using comprehensive data analysis and machine learning techniques.

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