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A STUDY ON OPTIMIZING TRAFFIC SIGNAL CONTROL FOR IMPROVED TRAFFIC FLOW

İYİLEŞTİRİLMİŞ TRAFİK AKIŞI İÇİN TRAFİK SİNYAL KONTROLÜNÜN OPTİMİZE EDİLMESİ ÜZERİNE BİR ÇALIŞMA

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ABSTRACT

Addressing traffic congestion holds paramount importance due to its severe economic and environmental repercussions. This study introduces an approach to address this pervasive issue by employing a wide-area control strategy for diverse road networks. The strategy leverages a dynamic offset control method and a multi-agent model to create a unique solution. In this framework, individual intersections function as distinct agents, engaging in negotiations, establishing connections, and forming a dynamic offset control zone resembling a tree structure. Within this structure, agents collaboratively manage green wave synchronization based on real-time traffic conditions at the network boundaries. To evaluate the effectiveness of this approach, comprehensive tests utilize both a simulated road network (Experiment 1) and an actual grid-like road network (Experiment 2). In Experiment 1, the proposed method consistently reduces lost time, resulting in an average reduction of 15% across all scenarios. Experiment 2 demonstrates a reduction in lost time across various intervals, with an impressive average reduction of 34% in lost time across all scenarios. These results demonstrate the strategy's ability to dynamically and adaptively establish green waves that significantly enhance traffic flow. In conclusion, this study demonstrates that the proposed method autonomously conducts offset control, effectively contributing to the smooth flow of vehicles.

Keywords: Traffic congestion, dynamic offset control, multi-agent model, green wave control, traffic flow enhancement

ÖZET

Trafik sıkışıklığının giderilmesi, ciddi ekonomik ve çevresel yansımaları nedeniyle büyük önem taşıyor. Bu çalışma, çeşitli yol ağları için geniş alanlı bir kontrol stratejisi kullanarak bu yaygın sorunu çözmeye yönelik bir yaklaşım sunmaktadır. Strateji, benzersiz bir çözüm oluşturmak için dinamik bir dengeleme kontrol yönteminden ve çok etmenli bir modelden yararlanır. Bu çerçevede bireysel kesişimler, müzakerelere katılan, bağlantılar kuran ve bir ağaç yapısına benzeyen dinamik bir dengeleme kontrol bölgesi oluşturan ayrı aktörler olarak işlev görür. Bu yapı içerisinde aracılar, ağ sınırlarındaki gerçek zamanlı trafik koşullarına dayalı olarak yeşil dalga senkronizasyonunu işbirliği içinde yönetir. Bu yaklaşımın etkinliğini değerlendirmek için, kapsamlı testler hem simüle edilmiş bir yol ağını (Deney 1) hem de gerçek ızgara benzeri bir yol ağını (Deney 2) kullanır. Deney 1'de önerilen yöntem, kayıp zamanı sürekli olarak azaltarak tüm senaryolarda ortalama %15'lik bir azalmaya yol açtı. Deney 2, tüm senaryolarda kayıp sürede ortalama %34'lük etkileyici bir azalmayla, çeşitli aralıklarla kayıp sürede bir azalma olduğunu göstermektedir. Bu sonuçlar, stratejinin trafik akışını önemli ölçüde artıran yeşil dalgaları dinamik ve uyarlanabilir bir şekilde oluşturma yeteneğini göstermektedir. Sonuç olarak bu çalışma, önerilen yöntemin otonom olarak ofset kontrolü gerçekleştirdiğini ve araçların düzgün akışına etkili bir şekilde katkıda bulunduğunu göstermektedir.

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Anahtar Kelimeler: Trafik sıkışıklığı, dinamik ofset kontrolü, çok etmenli model, yeşil dalga kontrolü, trafik akışı geliştirme

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INTRODUCTION

Traffic congestion is a condition where the volume of vehicles on a road network exceeds its capacity, resulting in slower traffic flow, longer travel times, and often complete standstills. It is a significant urban transportation problem characterized by reduced mobility, environmental harm, and economic costs. Congestion leads to increased fuel consumption, lost productivity, and additional maintenance expenses for vehicles. Moreover, it contributes to air pollution, greenhouse gas emissions, and adverse health effects due to prolonged exposure to traffic-related pollutants. It also has a negative impact on the quality of life, causing stress and reducing leisure time for residents of congested areas (Abdurakhmanov, R., 2022).

Addressing traffic congestion is vital for several reasons. It has a substantial economic impact, resulting in lost productivity and increased operating costs for businesses. It can also discourage investment and economic growth in congested regions. From an environmental standpoint, congestion contributes to air pollution and worsens climate change by increasing greenhouse gas emissions. It has public health implications, as it can lead to stress and health issues such as cardiovascular and respiratory problems. Reducing congestion improves the efficiency of transportation networks, facilitating the movement of people and goods, which, in turn, boosts economic activity. Congestion management is an integral part of urban planning, ensuring the development of livable and sustainable cities (Cao et al., 2022; Alsaawy et al., 2022). It also promotes equity by providing equitable access to jobs, education, and services for all members of the community. In essence, addressing traffic congestion is crucial for creating more efficient, environmentally friendly, and socially inclusive urban environments.

Traffic congestion has emerged as a pressing concern, attributed to the escalating traffic demand on road networks resulting from increased motorization and economic growth (Yang, 2023). Given the detrimental effects of traffic on pollution, resolving congestion holds significant importance. Extensive research efforts are underway to enhance traffic signal control and augment the processing capacity of existing road networks for improved traffic flow (Babaei et al., 2023; Abdurakhmanov, R., 2022).

Signal control parameters encompass cycle length, split, and offset, among others. This study focuses on offset control, which refers to the phase difference between adjacent signalized intersections (Alsaawy et al., 2022). Effective control of offsets can minimize the frequency of vehicle stops at red lights. Notably, approaches such as GreenWave (Yuan and Zheng, 2022; Cao et al., 2022) prioritize offset control to optimize directional traffic flows. In recent years, the concept of Bidirectional Green Wave (Zhu et al., 2023; Karimov, 2023), which facilitates synchronized traffic flow in both directions, has been proposed. Additionally, offset control methods utilizing real-time traffic information through intersection communication have gained prominence (Ji and Cheng, 2022).

One notable example of early online control is proposed by Soon et al. (2019), which employs statistical parameter design and fine-tuning based on sensor data. While these methods continue to be widely utilized, recent years have witnessed an increase in proposals for more dynamic or real-time offset control techniques. One such proposal involves a distributed control method that divides the mixed integer linear programming problem into intersections, with the objective function centered on the link queue length (Ma and He, 2019; Khamis and Gomaa, 2014).

Numerous control methods have been suggested for determining the offset value (Yang and Yang, 2022). However, most of these methods concentrate on fixed control target areas, predominantly focusing on single arterial roads (Lu et al., 2022; Wu et al., 2014). Addressing this limitation, this study introduces an online offset control model that dynamically constructs offset control areas on a road network using a multi-agent model.

The proposed method operates on the fundamental principles of GreenWave. A tree structure is established, primarily focusing on intersections with high traffic concentration, and the offset values are determined based on directional traffic flows. Experiments conducted using both a simulated grid-like road network and an existing road network showcased the dynamic and autonomous capabilities of the proposed method in constructing GreenWave. Furthermore, it demonstrated a remarkable efficacy in smoothing traffic flow compared to the existing control system in France.

The urgency of mitigating traffic congestion is underscored by its far-reaching consequences on the environment and daily life. The evolution of offset control methods, as evidenced by this study, highlights the ongoing pursuit of innovative solutions to enhance traffic flow and reduce congestion, ultimately contributing to more sustainable and efficient urban transportation systems.

The contributions of this study to the literature can be summarized as follows:

Comprehensive Understanding of Traffic Congestion: This study provides a comprehensive overview of traffic congestion, outlining its multifaceted nature, including its impact on mobility, economics, environment, and public health. It sets the stage for understanding the urgency of addressing this urban transportation challenge.

Focus on Offset Control: The study emphasizes the importance of offset control as a key parameter in traffic signal management. It highlights how effective offset control can alleviate congestion by reducing unnecessary stops at traffic lights, thus improving traffic flow.

Exploration of Innovative Solutions: By introducing an online offset control model that employs a multi-agent approach, the study delves into innovative solutions for addressing congestion. It breaks away from traditional fixed-control methods and explores dynamic, real-time approaches.

Application of GreenWave Principles: The study builds on the fundamental principles of GreenWave, a well-established concept in traffic management. It adapts these principles to develop a dynamic offset control strategy that can be applied in various road network scenarios.

Empirical Evidence: Through experiments conducted in both simulated and real-world road network settings, the study provides empirical evidence of the effectiveness of the proposed online offset control model. This empirical validation contributes to the practicality and applicability of the research findings.

In summary, this study not only serves as a comprehensive primer on traffic congestion but also introduces innovative offset control strategies and provides empirical support for their effectiveness. It contributes to the ongoing discourse on congestion management, offering valuable insights and solutions for creating more sustainable and efficient urban transportation systems.

The structure of the paper is as follows: Problem statement is presented in Section 2, the proposed method is proposed in Section 3. The evaluation experiments and results are given in Section 4. And finally, the conclusion and outlook part is given in Section 5.

PROBLEM STATEMENT

The challenge of traffic congestion presents significant economic and environmental implications (Wang and Hussain, 2021). Traffic congestion occurs when the road's capacity to facilitate smooth traffic flow is exceeded by the volume of vehicles, leading to increased travel times, elevated fuel consumption, and higher emissions, resulting in substantial economic losses and environmental harm (Tobita and Nagatani, 2013).

The focus of this study lies in the optimization of traffic signal control, a critical strategy for congestion mitigation (Chen and Chang, 2016). To effectively implement offset control using GreenWave, it is imperative that a consistent cycle length is maintained across all signalized intersections (Tobita and Nagatani, 2013). The cycle length, signifying the duration of a complete sequence of signal phases at an intersection, including green and red phases, is crucial for the success of GreenWave-based traffic signal coordination, as it ensures the smooth progression of vehicles through the network.

To establish this uniform cycle length, the unique characteristics of each intersection are considered, including link distances, system speeds, the number of vehicles entering from specific links, and the traffic capacity of the intersection per cycle (Wang and Hussain, 2021). These factors play a pivotal role in determining the optimal cycle length and, consequently, the effectiveness of offset control in enhancing traffic flow.

Therefore, the central problem addressed in this research is the strategic optimization of traffic signal control, with a specific focus on the establishment of a consistent cycle length across various signalized intersections, aiming to alleviate traffic congestion and enhance the overall efficiency of the road network. This approach seeks to minimize travel times, reduce fuel consumption, and mitigate environmental impacts, contributing to a more sustainable and economically viable transportation system.

In Figure 1, the adjacent signalized intersections (Wang and Hussain, 2021) are depicted at the bottom, and the variables are defined as follows:

$l_{(i,j)}$ represents the link distance between i and j.
$v_{(i,j)}$ denotes the system speed between i and j.
$p_{(i,j)}$ represents the number of vehicles entering from link i->j to intersection i in a single cycle.
Cap_i is traffic capacity of intersection i per cycle.
$Cap_{(ij)}$: indicates the traffic capacity of intersection i per cycle, encompassing the traffic capacity of link $i \to j$ per cycle.
For this research, the traffic capacity is calculated as 0.5 $veh.lane^{-1}.s^{-1}$.
Let J represent the set of intersections adjacent to intersection i. The total number of vehicles entering intersection i during one cycle is defined by Equation 1.

$$P_i = \sum_{j \in J} p(j,i) \tag{1}$$

To implement offset control using GreenWave, it is essential to ensure that the cycle length remains consistent across all intersections (Tobita and Nagatani, 2013). In alignment with the methodology employed in this study, where GreenWave is utilized, it is assumed a uniform cycle length for all intersections under control (Chen and Chang, 2016). This means that the duration of green and red phases at each signalized intersection is synchronized to be the same, ensuring that vehicles progress smoothly through the network. The need for a uniform cycle length arises from the core principles of GreenWave, where the coordination of traffic signals relies on synchronized timing.

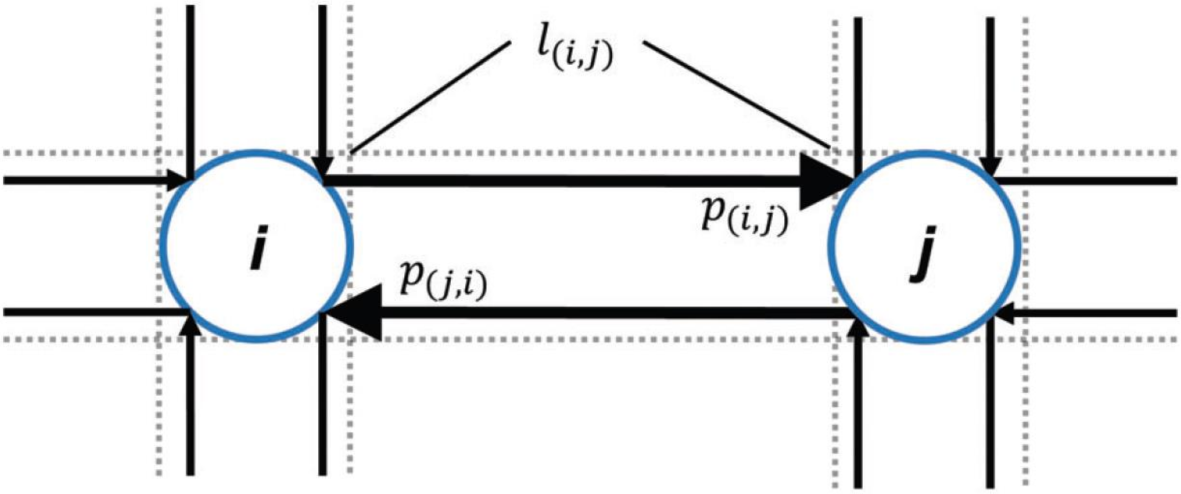

Figure 1. Two Adjacent Intersections

PROPOSED METHOD

In this method, each signalized intersection is virtually assigned an agent. In addition to the information outlined in the Problem Statement section, the agent is assumed to have access to the signal schedule information. Control operations are executed based on the information surrounding the assigned intersection.

The agent assesses the level of traffic congestion at the assigned intersection, determining whether the application of offset control is warranted. It's important to note that while the offset value is always present, the agent's role involves dynamic adjustments to this value based on real-time traffic conditions.

If the agent deems offset control necessary, it initiates negotiations with neighboring intersections to establish cooperative measures. Through a series of actions, the agent dynamically constructs an organizational framework for collaborative control and conducts offset control within this framework.
Furthermore, when it is determined that the degree of traffic congestion has significantly reduced, coordinated control is concluded.

Agent Configuration

Each agent is constantly in one of the five following states (modes):
Isolation: A state characterized by non-coordination.
Root: The central state of cooperative control.
Sub-Root: A state in which the agent serves as a component of the area.
Clearance Root: A state occurring just before the Root agent concludes cooperative control.
Clearance Sub-Root: The state immediately preceding the conclusion of cooperative control by the sub-agent.

Collaborative Functions

Let A_i represent the agent at a specific intersection, and A_j denote the agent at an adjacent intersection j to intersection i. If A_i is a Sub agent, A_i^R refers to the root agent of the organization to which A_i belongs.

Root Generation

The Isolation agent verifies the satisfaction of Eq. 2 by the Sub agent and confirms if Eq. 3 is met to determine whether a transition to the Root agent is required. This assessment is conducted on a per-cycle basis. In this context, α denotes a constant, and P_R^i represents the total number of vehicles entering the intersection where A_R^i is positioned.

$$P_i > \alpha Cap_i \tag{2}$$
$$P_i > P_R^i \tag{3}$$

Negotiation

Once A_i transitions to the Root mode, it initiates a cooperative proposal to its neighbouring agent A_j when Eq. 4 is fulfilled. In this context, β represents a constant.

If A_j is in the Isolation mode, the proposal is unconditionally accepted. If A_j is in the Sub mode, the proposal is accepted only when Eq. 5 is met. Lastly, if A_j is in the Root mode, the proposal is accepted provided Eq. 6 is satisfied.

$$P_i > P_R^j \tag{5}$$
$$P_i > P_j \tag{6}$$

If the proposal is accepted, A_j undergoes a transition to the Sub mode with A_i as its parent. During this process, the relative offset between the two agents is computed. However, if the proposal is not accepted, A_j remains unchanged.

Propagation

The Sub mode is activated by A_j's change. When Equation 7 is satisfied, a collaborative proposal is made to the neighboring agent, A_k. However, if A_k is already affiliated with A_R^j, the cooperative performance is not allowed.

$$\left(p(j,k) > \beta Cap_{(j,k)}\right) \vee \left(p(j,k) > \beta Cap_{(j,k)}\right) \tag{7}$$

If the Isolation mode is active for A_k, the proposal is unconditionally accepted. If the Sub mode is active for A_k, the proposal is accepted if Equation 8 is satisfied. If the Root mode is active for A_k, the proposal is accepted if Equation 9 is satisfied.

$$P_R^j > P_R^k \tag{7}$$
$$P_R^j > P_k \tag{8}$$

If the proposal is accepted, A_k is switched to Sub mode with A_k as the parent. At this point, the relative offset between the two is calculated. If the proposal is not accepted, A_k remains unchanged. Following that, the cooperative proposal continues to propagate until it becomes completely unacceptable, forming a tree structure around the initiating agent and the subagents that have accepted the proposal. Offset control is executed within the organization formed in this manner.

Organization Dissolution

When Equation 10 is satisfied by the root agent, it is determined that traffic concentration has been reduced, and organization dissolution is carried out. In this equation, θ represents a constant, and $\overline{P_i}$ denotes the average number of vehicles entering the root agent over the past few cycles.

$$\overline{P_i} < \theta Cap_i \tag{10}$$

The message regarding the dissolution of the organization propagates throughout the entire organization in a chain reaction. Consequently, the Root mode agent is switched to ClearanceRoot mode, while the Sub mode agent is switched to ClearanceSub mode. After offset cancellation based on the ClearanceRoot agent, the ClearanceSub agent transitions to the Isolation mode. Similar to the Isolation agent, both the ClearanceRoot agent and the ClearanceSub agent assess changes to the Root mode. If they receive a collaborative proposal, they accept it unconditionally.

Offset Control

Within the organized structure, the offset is computed by each agent for every cycle. Considering adjacent intersections i and j, where i serves as the parent agent and j as the child agent. Furthermore, considering the values $p(i,j)$ and $p(j,i)$, the larger value is designated as p_l, and the smaller value as p_s. The traffic volume deviation r for each direction is then determined using Equation 11.

$$r = \frac{p_l}{p_s} \tag{11}$$

Table 1. The Inflows of Vehicles for the Experiment 1

	Vehicle inflow ($veh/h.each\ row$)	
time (s)	West-East	East-West
0-7200	1000	0
7200-7800	0	0
7800-15000	0	1000

The duration of two hours of traffic flow and 30-minute pauses is chosen to simulate different traffic scenarios that encompass peak and off-peak traffic periods. This approach allows to evaluate the effectiveness of our offset control strategy under various traffic conditions.

Next, the absolute value O_r of the relative offset is calculated by Equation 12. Here, γ, δ $(\gamma > \delta \geq 1)$ are constant threshold values.

The threshold values γ and δ, as mentioned in the equations, play a significant role in determining the relative offset O_r and, subsequently, the cycle start time t_j at intersection j. Here's an explanation of these threshold values:

Threshold Value γ: This threshold value, denoted as γ, serves as a crucial parameter in the calculation of the relative offset O_r when determining whether to adjust the offset. When the relative offset r exceeds this threshold ($r \geq \gamma$), it triggers the calculation of O_r using the formula: $O_r = \frac{l_{(i,j)}}{v_{(i,j)}}$. In this context, γ acts as a criterion for evaluating whether the traffic conditions, as indicated by r, warrant a change in offset.

Threshold Value δ: δ is another threshold value, and it is used in conjunction with γ to calculate O_r when the relative offset falls within a certain range ($1 \geq r \geq \gamma$). Specifically, when r falls within this range, O_r is calculated using the formula: $O_r = \frac{r-\delta}{\gamma-\delta}$. δ helps define a transitional region where offset adjustments are considered. It represents the lower boundary of the range within which offset changes are gradually introduced.

These threshold values, γ and δ, are integral to the offset control algorithm, as they determine the conditions under which offset adjustments are made. γ represents a higher threshold, signifying more substantial changes in offset, while δ defines a transitional zone where offset adjustments are moderate. The choice of these threshold values depends on the specific traffic conditions and the desired level of offset control responsiveness.

$$O_r = \begin{cases} \dfrac{l_{(i,j)}}{v_{(i,j)}}, & (r \geq \gamma) \\ \dfrac{l_{(i,j)}}{v_{(i,j)}} \dfrac{r-\delta}{\gamma-\delta}, & (1 \geq r \geq \gamma) \\ 0, & (r \leq 1) \end{cases} \tag{12}$$

The relative offset $O_{(i,j)}$ from A_i to A_j can be calculated by Equation 13.

$$O_{(i,j)} = \begin{cases} O_r, & (p_{(i,j)} > p_{(j,i)}) \\ -O_r, & (p_{(i,j)} \geq p_{(j,i)}) \end{cases} \tag{13}$$

Finally, the cycle start time t_j at intersection j is derived from Equation 14. Here, t_i represents the start time of the next cycle at intersection i, and $split_i$ denotes the duration of time allocated for the indication of the corresponding direction at intersection i.

$$t_j = t_i + O_{(i,j)} + split_i \tag{14}$$

In summary, γ and δ are key parameters in the offset control algorithm, helping to evaluate and regulate offset adjustments based on the relative offset r between intersections. Their values are carefully chosen to strike a balance between maintaining traffic flow efficiency and adapting to changing traffic conditions.

EVALUATION EXPERIMENT

Two experiments are conducted to examine the feasibility of dynamic offset control by the proposed method and its effectiveness.

In the current signal control used for comparison, the offset variation is limited to 25% of the cycle length per cycle. Therefore, when an offset exceeding the variation limit is calculated in the evaluation experiment, this variation is reflected in several cycles.

Experiment 1: Grid Road Network

A comparative experiment is conducted on a grid road network consisting of 5 rows and 5 columns, where signal control without offset control is employed. Both the proposed method and the comparative method have a cycle length of 90 seconds. Table 1 presents the count of inflow vehicles.

Experiment 2: Real Area Network

A comparative experiment is conducted on a road network that replicates an actual area in Clermont-Ferrand Prefecture, as depicted in Figure 2. The intersections to be controlled are represented by red circles in Figure 2, with a total of 16 locations.

For the control parameters, the values utilized in the current control at the site are employed. However, due to the constraint of offset control, the cycle length is standardized to 120 seconds for all intersections, using only the proposed method.

Table 2 displays the count of inflow vehicles. In this context, R_1, R_2, and R_3 denote the routes $B \rightarrow F \rightarrow A, D \rightarrow G \rightarrow C$, and $E \rightarrow G \rightarrow F \rightarrow A$, respectively.

Additionally, the reverse routes are indicated by primed symbols, such as R_1'.

Simulation Parameters

In this study, the experiment utilized SUMO (Simulation of Urban Mobility). As the method proposed in this paper focuses on offset control, a uniform value for the split duration is employed across all methods.

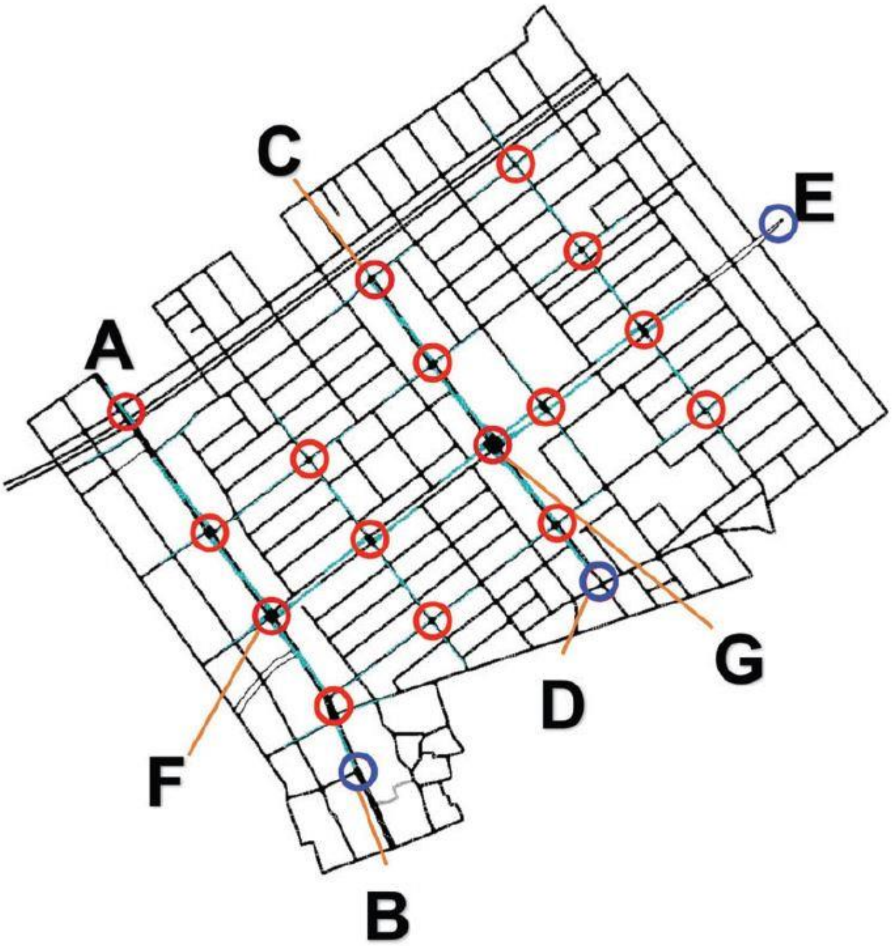

Figure 2. The Simulated Area

Table 2. The Inflows of Vehicles for the Experiment 2

	Vehicle inflow (veh/h)		
time (s)	R_1	R_2	R_3
0-7200	1350	1350	500
7200-7800	0	0	0
	R_1'	R_2'	R_3'
7800-15000	1350	1350	500

For the parameters used in Equations 2, 4, 10, and 12, the values of Equation 15 are used.

$$\begin{pmatrix} \alpha \\ \beta \\ \gamma \\ \delta \\ \theta \end{pmatrix} = \begin{pmatrix} 0.4 \\ 0.15 \\ 1.5 \\ 1.1 \\ 0.8 \end{pmatrix} \tag{15}$$

In the study, an investigation within the Clermont-Ferrand Prefecture is conducted, focusing on a critical main road and its associated intersections, where the traffic volume data over a 2-hour duration is collected. This main road spans approximately 10 kilometers within the Clermont-Ferrand Prefecture.

Experimental Results

In this study, the effectiveness is assessed based on vehicle lost time.

Figure 3 illustrates the average loss time progression in Experiment 1, while Figure 4 presents the average loss time progression in Experiment 2. Furthermore, Table 3 provides statistical values for the entire scenario in each experiment.

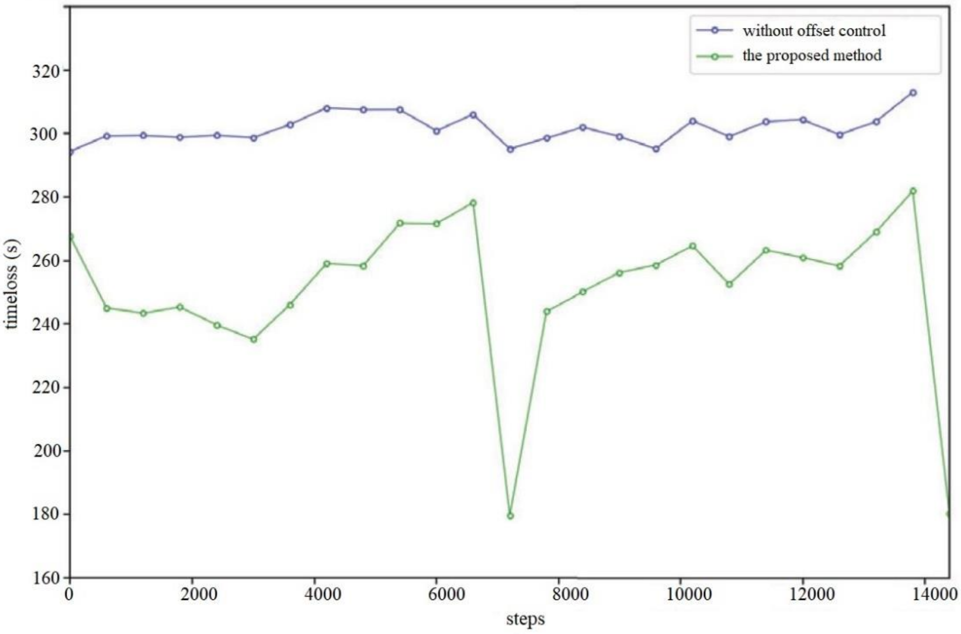

Figure 3. Variation of Average Loss Time for Experiment 1

For Experiment 1, the proposed method consistently reduced lost time throughout the duration, as depicted in Figure 3. Moreover, as indicated in Table 3, the proposed method achieved an average reduction of 15% in lost time across all scenario variations.

In Experiment 2, the proposed method exhibited a reduction in lost time across almost all time intervals, as demonstrated in Figure 4. Additionally, according to Table 3, the proposed method yielded an average reduction of 34% in lost time across all scenarios within the actual area of rice fields.

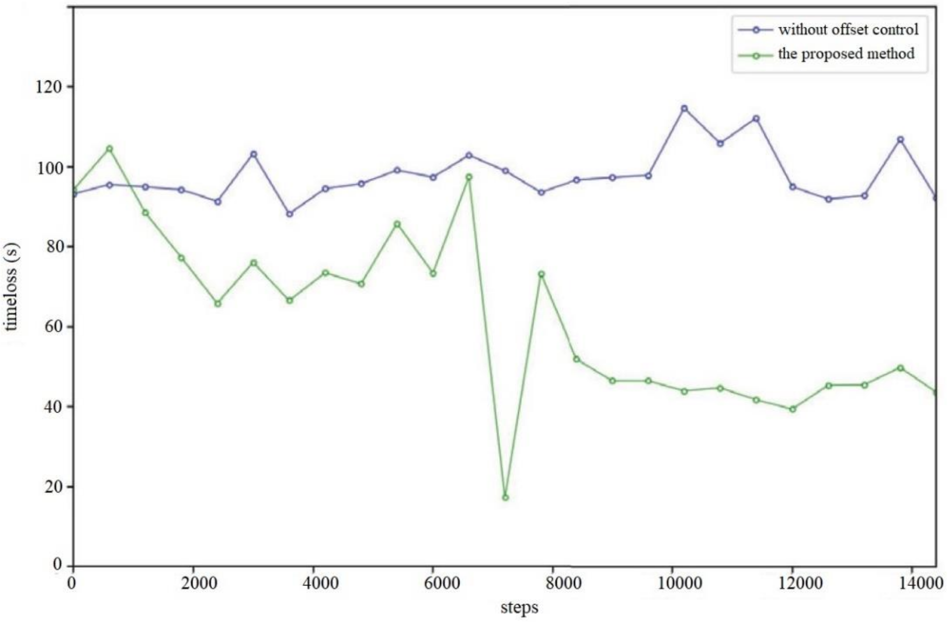

Figure 4. Variation of Average Loss Time for Experiment 2

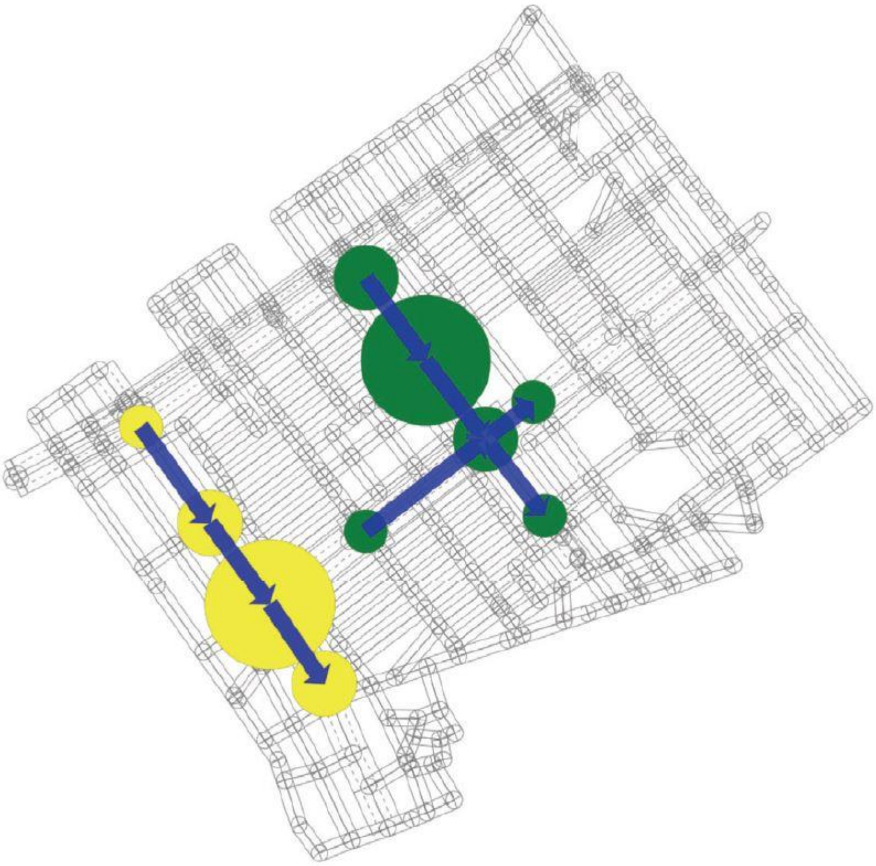

Figure 5. The Visualisation of Organization of Experiment 2

Figure 5 offers a visualization of a specific instance depicting agent tissue formation and offset control in Experiment 2. The coloured circles represent Root or Sub mode agents, signifying their affiliation within the same organization. The arrows in the figure indicate the execution of offset control, prioritizing the direction indicated by each arrow. This visualization confirms the seamless operation facilitated by the proposed method.

Based on the above findings, it is evident that the proposed method autonomously performs offset control and effectively contributes to the smooth flow of vehicles.

CONCLUSION AND OUTLOOK

In this study, a dynamic offset control method utilizing a multi-agent model is proposed with the objective of enhancing traffic flow. The aim is to enable autonomous construction of control areas by groups based on prevailing traffic conditions. The concept of GreenWave, widely employed in current practices, served as the control standard for the agents in this research.

Through simulation experiments, it is demonstrated that the proposed method effectively autonomously performs offset control, establishes GreenWave patterns, reduces vehicle loss time, and improves traffic flow.

Looking ahead, future prospects encompass the exploration of various related approaches such as offset optimization methods and traffic condition prediction, which have emerged in recent years. It is conceivable that the model proposed in this study, which autonomously constructs control areas, could be further developed by integrating alternative offset control standards beyond GreenWave and leveraging predictive information for traffic condition assessment. This holds promise for advancing the field of traffic control and optimization.

In the realm of Cooperative Intelligent Transport Systems, various avenues offer opportunities for advancements in addressing traffic congestion and optimizing traffic signal control. These include advanced data analytics, machine learning and artificial intelligence techniques, cooperative strategies, integration of transportation modes, network-wide optimization approaches, and the integration of emerging technologies such as connected and autonomous vehicles. Scalability, adaptability, and real-world pilot studies are essential considerations for implementing and evaluating these strategies.

Additionally, comprehensive cost-benefit analysis is crucial to quantify the economic, environmental, and societal impacts of different traffic signal control approaches. This analysis will assist in decision-making processes and prioritize strategies based on their value and benefits.

By delving into these areas of research and development, the field of traffic signal control for Cooperative Intelligent Transport Systems can continue to evolve. These efforts hold the potential to create more efficient, sustainable, and congestion-free transportation networks, ultimately improving the quality of life for individuals and societies alike.

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