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Smart Roundabout Coordination Systems for Sustainable Urban Mobility

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Abstract

Traffic signal coordination control is a smart approach used in urban networks to relieve the congestion by increasing corridor throughput and minimizing overall traffic delay. Previous studies have investigated various signal coordination challenges; however, integrating roundabouts into a coordinated signalized corridor without compromising their operational distinctiveness remains underexplored. This study introduces an adaptive traffic signal offset strategy incorporating a platoon compaction factor to address the dispersion effects caused by roundabouts, ensuring the preservation of platoon movement along the coordinated corridor. The method was evaluated using the PTV VISSIM micro-simulation software. The results show improvements in sustainability indicators at roundabouts, with average corridor-level delays minimized by 17%, delays associated with vehicle stops reduced by 28%, fuel consumption reduced by 16%, and emissions reduced by 9% and 16% for NO_x and CO_2, respectively. These improvements were statistically significant, affirming the robustness of the proposed method. The findings underscore the potential benefits of implementing this framework in real-world traffic scenarios, contributing to making urban transportation systems more efficient and sustainable.

Keywords: Roundabouts; Traffic Signal Coordination; Sustainable Traffic Management; Intelligent Transportation Systems (ITS); Smart Mobility; PTV VISSIM.

1. Introduction

Traffic congestion in metropolitan cities is an escalating challenge that is driven by the rapid increase in automobile ownership and population density. This problem results in longer travel times, higher fuel consumption, increased greenhouse gas emissions, and a decline in the overall quality of urban life [1-3]. Advanced Traffic Management Solutions (ATMS) have been developed to address these challenges, with particular focus on at-grade intersections, which often act as bottlenecks in transportation networks. Traffic signal coordination, an impactful strategy to tackle the aforementioned challenges, offers considerable benefits, particularly in high-traffic corridors [4]. It reduces delays for vehicle platoons, lowers emissions, eases traffic congestion, and improves air quality [5-7], compared to uncoordinated signals.

The use of roundabouts is another widely adopted strategy for managing traffic at at-grade intersections. While roundabouts require more space than traditional intersections, their distinctive design reduces the number of conflict points and lowers vehicle entry speeds. Consequently, roundabouts are a safer alternative to at-grade signalized intersections for both automobiles and pedestrians [8-10]. Additionally, roundabouts outperform signalized intersections in handling low to moderate traffic levels [11, 12], as they reduce vehicle delays, fuel consumption, greenhouse gas emissions, and noise levels [11-15].

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Both signal coordination and roundabouts offer distinct advantages for traffic management. While the combined use of roundabouts and signalized intersections is becoming increasingly common to leverage their respective strengths, integrating roundabouts into coordinated signalized corridors presents considerable challenges. A key issue lies in balancing the operational efficiency of signalized systems with the random flow patterns often associated with roundabouts.

The literature consistently highlights the platoon dispersion problem caused by roundabouts. Vehicles discharging from roundabouts often display irregular flow patterns compared to other intersection types, which increases platoon dispersion and challenges in signalized network coordination [9]. Studies indicate that the randomness of vehicle discharge disrupts traffic progression when a roundabout is introduced within a signalized corridor, which reduces signal coordination efficiency [16-18]. Even a single roundabout can cause breakdowns in traffic platoons, interrupting smooth movement [9]. To address these challenges, experts have recommended signalizing major approaches to roundabouts and coordinating them with upstream and downstream intersections [9]. However, this approach can compromise the unique advantages of roundabouts, particularly their ability to maintain continuous traffic flow.

Meanwhile, the importance of vehicle platooning for traffic coordination efficiency is well-documented in the literature. Goldmines & Skabardonis [19] and Matros et al. [20] emphasize that maintaining platoons is critical for optimizing traffic signal coordination and ensuring efficient corridor operations. According to the Traffic Signals Manual (TSM) [21], minimizing platoon dispersion significantly reduces traffic queues, especially during peak hours, by allowing more vehicles to pass through intersections during each green phase.

Platoon dispersion plays a pivotal role in signal timing optimization [20]. Accurately predicting platoon size and dispersion is vital to determining the need for signal coordination and optimization of signal timing plans [20]. Models that incorporate platoon dispersion provide better predictions of traffic flow and enhance signal coordination [22]. Integrating platooning strategies with traffic signal control at intersections, including roundabouts, can maximize traffic flow, reduce travel times, and lower fuel consumption by aligning signal phases with platoon movements [23].

This research addresses a critical gap by focusing on the integration of roundabouts into coordinated signal systems while preserving their operational advantages. Unlike prior studies, which primarily discourage roundabout integration in signalized corridors or propose signalization at roundabout approaches, this study introduces a framework for mitigating platoon dispersion. It proposes a framework to enhance traffic management efficiency by regulating coordinated traffic signals on arterials with roundabouts. This is achieved through adaptive signal offsets that consider the dispersion caused by roundabouts, thereby preserving platoon integrity throughout the coordinated arterial. The proposed approach was evaluated based on its impact on travel time, fuel consumption, and emissions.

The remainder of the article is organized as follows: Section 2 provides a brief review of relevant topics, and Section 3 describes the proposed method. Section 4 provides an evaluation of the framework in a microsimulation environment, and Section 5 presents and discusses the results of the case studies. Finally, Section 6 concludes the paper.

2. Literature Review

Efficient traffic signal control is essential for managing vehicle flow, reducing congestion, minimizing accidents, and optimizing travel times. Building on the advantages of traffic signal control, signal coordination, also known as synchronized traffic signals, offers significant improvements in urban traffic management.

Coordination enables the synchronization of several intersections to regulate specific movements in a network [24], enabling a platoon of vehicles to pass through several intersections without halting. Coordinated signal control presents a promising alternative for a sequence of intersections along a road, as it provides greater capacity [25]. The primary advantages of signal coordination include reductions in delays by reducing the travel time and the number of stops along the coordinated directions [26-28]. Furthermore, a well-designed progression plan is conducive to reducing fuel consumption and vehicle emissions [29].

A key measure that reflects the effectiveness of traffic signal coordination is the reduction of stops and an improvement in the movement of platooning vehicles. Therefore, platoon dispersion, the phenomenon in which vehicle groups (platoons) spread out as they move through a traffic network, poses a significant challenge [30]. It results in inefficient traffic flow and increased delays at intersections. Therefore, effective coordination strategies are essential to mitigate dispersion and ensure that vehicles remain grouped, enabling them to pass through intersections during green phases and thereby reducing stops and delays [31].

Several studies have investigated the coordination between platooning vehicles and traffic signals, emphasizing its importance [23]. TSM [21] highlights that reducing platoon dispersion can substantially alleviate traffic congestion, particularly during peak hours, by enabling a greater volume of vehicles to pass through intersections during each green signal phase. Similarly, studies [19, 20] emphasize the importance of maintaining vehicle platoon formation to optimize signal coordination. When vehicles travel in tightly grouped platoons, traffic signals can be timed to allow the groups to pass through multiple intersections without stopping. This coordination reduces the likelihood of vehicles encountering red lights, thereby decreasing stop-and-go driving patterns, which contribute to congestion and increased fuel consumption.

In addition to traffic signal coordination, roundabouts present an effective method to improve traffic flow in urban areas. These circular intersections facilitate counterclockwise traffic flow around a central island, reducing conflict points and promoting continuous movement. The design is particularly advantageous in urban settings. Research indicates that converting signalized intersections to roundabouts can reduce greenhouse gas emissions and fuel consumption by 21% and 28%, respectively [14]. This reduction is primarily achieved by minimizing idling, acceleration, and deceleration at traditional traffic lights. Additionally, roundabouts help mitigate noise pollution near road intersections [32]. Moreover, roundabouts play a crucial role in enhancing road safety by reducing the risk of motor-vehicle crashes and associated injuries. Studies have demonstrated that transforming traditional intersections into roundabouts significantly decreases the number of crashes resulting in injuries or fatalities [33, 34]. However, roundabouts become less competitive as the volume of traffic increases [35].

Roundabouts often face challenges related to the lack of coordination with surrounding traffic signals. Roundabouts located upstream of coordinated signalized intersections in metropolitan areas disperse platoons instead of forming them, resulting in ineffective signal coordination [18]. The primary objective of signal coordination is to move the platoon traffic between coordinated intersections with minimal stoppages.

Some studies have explored the impact of integrating roundabouts into major signalized corridors. For example, Krogscheepers & Watter [36] evaluated the effect of incorporating roundabouts in a high-speed and high-volume corridor, comparing them to a corridor with traffic signals. They used three levels of traffic demand for five intersections in a rural corridor and reported that the average speed was higher for the roundabout corridor during most times of the day for all three levels. They concluded that roundabouts could offer considerable benefits over traffic signals, based on their capacity. However, this study does not address the effect of roundabouts on traffic signal coordination, an essential factor in urban traffic management.

Expanding on the examination of roundabouts and signalized intersections, Bared & Edara [37] explored the effects of signalized intersections near roundabouts using a developed microsimulation model. They specifically examined how a coordinated signalized arterial (comprising three intersections) behaves when a roundabout is added to the corridor. Their findings indicate that average delay times are similar to those of signalized intersections when the roundabout operates below its capacity. However, under heavy traffic conditions, when the roundabout reaches its capacity, signalized intersections perform slightly better.

Hallmark et al. [18] utilized VISSIM microscopic simulation software to investigate the integration of roundabouts into signalized corridors. They assessed the effects of introducing a single roundabout into an existing signalized corridor, evaluating performance measures such as average travel time, stopped delay, and overall average delay throughout the corridor. Their case study on the S-69–Grand Avenue Corridor in Ames, Iowa, demonstrated that a signalized corridor with two through lanes at all intersections produced similar results, irrespective of the presence of a central roundabout. The authors concluded that the roundabout did not degrade the performance of the signalized corridor. However, the study did not consider varying demand levels and their impacts, suggesting that future research should address these factors to fully understand the potential benefits and challenges of such integrations.

To sum up, roundabouts facilitate continuous traffic flow and can reduce delays with random vehicle arrivals. However, they can disrupt traffic flow in corridors with coordinated signals and cause unnecessary queuing if placed upstream of signalized intersections [18]. Therefore, it is generally advisable to avoid placing unsignalized intersections between two coordinated signalized intersections, particularly when the goal is to minimize delays and maximize throughput along the arterial. Nonetheless, in certain situations, a roundabout is installed between two signalized intersections to leverage its enhanced safety features. In such cases, it is crucial to preserve both the roundabout operation and the coordination of traffic signals, which is the primary aim of this study.

Minimizing platoon dispersion is a key objective in traffic signal coordination. Maintaining vehicle groups to pass through intersections efficiently during green phases reduces stops and delays and enhances the overall traffic flow, safety, and fuel efficiency [38]. From this perspective, the main objective of this study is to fill a critical gap in the existing literature by proposing a comprehensive framework for traffic signal coordination in scenarios where a roundabout is situated within a network of coordinated traffic signals. This framework aims to dynamically mitigate the disruption of vehicle platoons owing to the presence of roundabouts, thereby enhancing the overall efficiency of traffic signal coordination.

3. Research Methodology

This research presents an innovative framework focused on adaptive offsets to maintain a progression band through a signalized arterial when a roundabout is located between signalized intersections.

Integrating a roundabout into a signalized arterial poses considerable challenges owing to the high variability in saturation discharge rates at roundabout entrances, which differ greatly from those at signalized intersections. Roundabouts generally have lower discharge rates, resulting in compact platoons near the entry and more dispersed platoons downstream. This dispersion can result in inefficient signal coordination along the corridor, making it difficult to maintain effective traffic flow [9, 39].

To overcome these challenges, the proposed framework incorporates a dynamic additive factor for platoon compaction (PC) into the offset equation. The primary objective is to ensure a consistently smooth progression band through the signalized arterial, minimizing stops and preserving platooning. The methodology relies on real-time data collected from detectors placed at the yield lines of roundabout entrances. These detectors provide crucial data on platoon behavior, enabling the system to dynamically adjust offsets in real time. The adopted control framework strategy is shown in Figure 1.

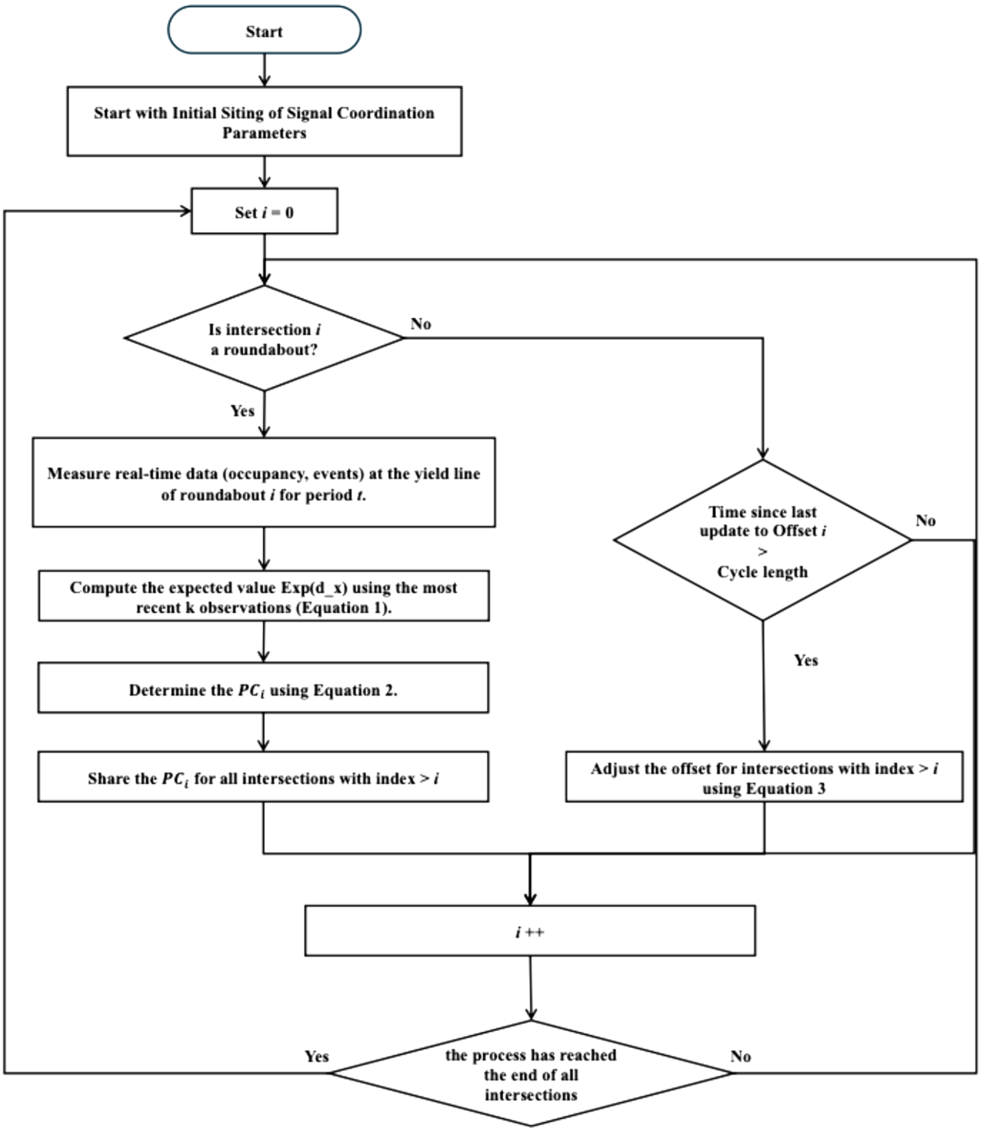

Figure 1. Adopted control framework strategy

3.1. Optimization of Initial Parameters

In traffic signal coordination, the primary parameters that need to be optimized after determining the coordinated route include cycle length, split distribution, and offset [24]. Several reliable and well-known models are available for optimizing cycle lengths and green splits at intersections [40-47]. Therefore, the proposed framework assumes that an optimization method has been applied to set the initial value of the coordination parameters.

Cycle length and split distribution are influenced by the demand at the intersection, whereas the speed between intersections affects the offset. Offsets, which represent the time relationship between the coordinated phases of consecutive traffic signals, are crucial for effective traffic signal coordination [24]. When vehicles travel in platoons, coordinating their movements becomes easier by focusing on the arrival of the platoon leaders at each intersection. Once the platoon leaders pass through the green light, the rest of the platoon typically follows without stopping. However, this assumption may not hold true in the presence of a roundabout. While predicting the arrival of the platoon leader is feasible, the rest of the platoon could be too dispersed to fully clear the next intersection in one green phase. This is the reason the proposed system adjusts the offset using the PC factor.

3.2. Platoon Compaction (PC)

Roundabouts (or unsignalized intersections) between signalized intersections introduce extra delay owing to the time required by drivers to search for a gap to enter and traverse the roundabout, along with the added deceleration and acceleration (Equations 2 and 3). The delay experienced by vehicles at the roundabout entrance can be estimated analytically using various models, such as the highway capacity manual. Additionally, vehicle delays (hold-ups) can be evaluated via real-time observation. This approach relies on the continuous detection of vehicles at the roundabout entrance (on the yield line) (Equation 1).

The expected delay at the roundabout entrance can be estimated using data from previous studies, historical records, or real-time data collected from detectors at the yield line. The estimation can be expressed using the following Equation:

$$Exp(d_x) = \frac{\mathrm{Occ\ (t)}}{\mathrm{EvOcc\ (t)}} + \mathrm{E(Del)} + \mathrm{E(Accel)}, \tag{1}$$

where E(Del) represents the expected deceleration time, E(Accel) represents the expected acceleration time, Occ(t) represents the total occupancy time at the targeted detector during period t, EvOcc(t) indicates the number of vehicles that occupied the detector during period t.

The additional delay at roundabouts affects the compaction of platoons moving through them, a delay that would not exist if the roundabout were signalized and the platoon of vehicles arrived during the green time. Therefore, platoon coordination (PC) is required at intersections downstream of the roundabout to address the disparity caused by it. Three main factors influence PC, as expressed in Equation 2. First, the disparity between the saturation discharge rates of intersections (hs) and roundabouts influences the platoon disparity before and after the roundabout. Second, the platoon size (P_{Size}) refers to the number of vehicles moving as a cohesive unit through the traffic network. Lastly, the factor γ is incorporated into the PC function to address the inherent variability in roundabout discharge rates, which can be attributed to factors such as vehicle type and size, driver behavior, and external conditions.

$$PC_{\ i} = \mathrm{P}_{Size}\ [Exp(d_X) - hs\ ] \times \gamma \tag{2}$$

3.3. Adaptive Proposed Offset

The proposed offset is dynamic and adaptive to consider variations in discharge rates at roundabouts and their effects on downstream coordination (Equation 3). A rolling horizon method was employed to capture the discharge rate in real time. It is a dynamic approach in decision-making in which the planning horizon moves forward in time as new data become available. The method can be used in scenarios where decisions must be made sequentially over time and regularly updated based on new information. Based on the concept of rolling horizon, the offset $\emptyset_i$ at time *t* is determined based on the most recent *k* observations of the discharge rate and a projection of discharge rates up to projection horizon periods into the future. The projection horizon must be shorter than the cycle length for coordinated traffic signals.

$$\emptyset_{i,K} = \ \mathrm{Mod}\left(\emptyset_{i,k=0}\ + \Delta PC_{i,k}, C\ \right) \tag{3}$$

Here, $\emptyset_{i,K}$ represents the estimated offset of intersection i in period K, $\emptyset_{j,K-1}$ represents the estimated offset of intersection j in period (K-1), and C indicates the cycle length.

4. Evaluation

The PTV VISSIM microsimulation software was used to evaluate the effectiveness and adaptability of the proposed framework. Several researchers have employed VISSIM as a platform to validate their proposed signalization logic [48-50]. Furthermore, Saha et al. [51] highlighted its capability to accurately estimate platoon dispersion under mixed traffic conditions, demonstrating the software's broad capabilities in traffic analysis. These features make VISSIM a suitable and reliable tool for evaluating the proposed framework in this study.

The architecture of the Traffic Simulation System, as implemented in VISSIM, is shown in Figure 2. The proposed framework was integrated into VISSIM via the Component Object Model (COM) interface, utilizing logic code in VAP and Python for data extraction and performance evaluation. The environmental impact was estimated using a motor vehicle emission simulator (MOVES) model, developed by the USEPA. MOVESTAR, an open-source vehicle fuel and emission model derived from the MOVES framework [50], was utilized to calculate pollutant emissions and fuel consumption for motor vehicles. The model produced second-by-second results for CO, HC, NOx, and CO2 emissions in grams.

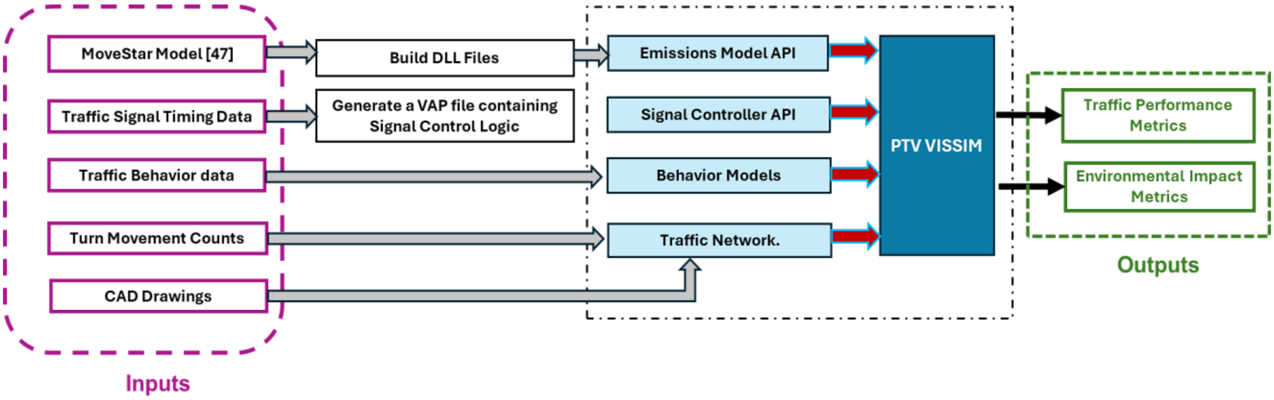

Figure 2. Architecture of the Traffic Simulation System Implemented in VISSIM

Moreover, key adjustments to the simulation parameters in the VISSIM model were made and are presented in Table 1. The VISSIM model developed for this study provides a detailed representation of the road network, enabling the simulation and analysis of traffic flow under various conditions. It incorporates a comprehensive layout of roads, intersections, and traffic control devices, accurately mirroring real-world infrastructure (see Figures 3 and 4).

Table 1. Key simulation parameters of the adopted VISSIM model

Simulation Parameter	Sub-Parameter	Value
Wiedemann 74 (Car Following Mode)	Average Standstill Distance	2.5
	Additive Part of Safety Distance	2.3
	Multiplicative Part of Safety Distance	3.4
Gap Acceptance (Conflict Area)	Front Gap	0.5
	Rear Gap	0.5
	Minimum Gap	3.2
	Safety Distance Factor	1.5
Desired Speed	General Speed	80
	Reduced Desired Speed	35
Simulation Resolution		10

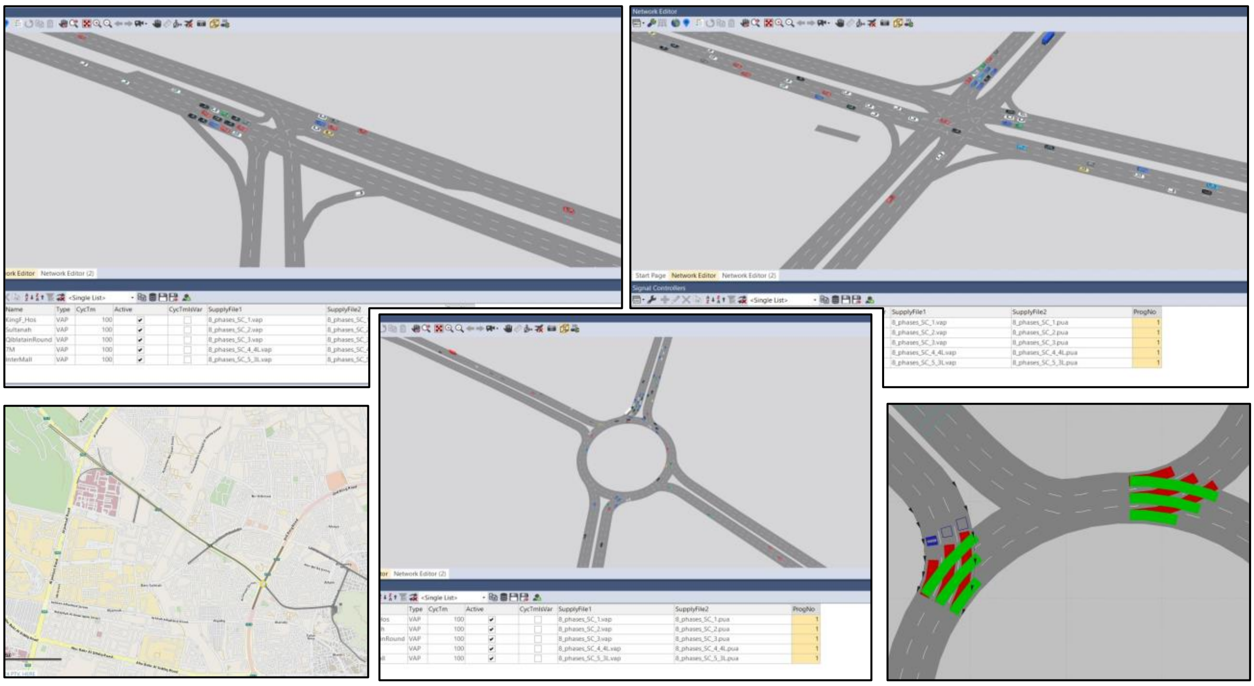

Figure 3. Screenshots of the Network Representation in VISSIM

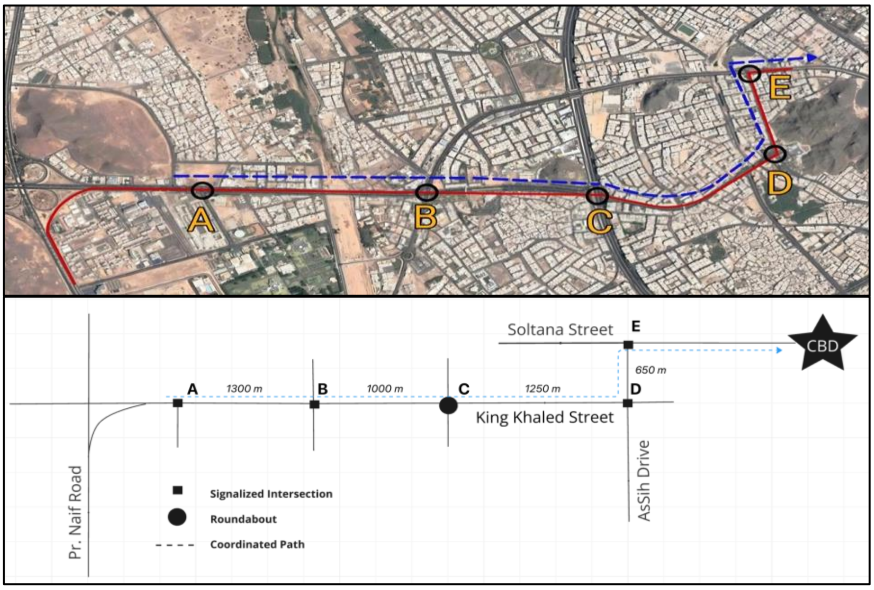

Figure 4. Layout of the study site King Khaled Street in Medina

The proposed system was evaluated using traditional coordinated traffic signal control on arterial roads as the base case. Emissions and traffic performance metrics—including emission rates, total delays, and delays caused by stops—demonstrated the effectiveness of the proposed method. A comprehensive sensitivity analysis was conducted to ensure robust and reliable outcomes. Various levels of congestion were analyzed by adjusting the observed turn-movement counts from April 2020 (see Table 2) both upward and downward. Factors of 0.85, 1.0, 1.4, and 1.6 were applied to modify the demand for scenarios 1, 2, 3, and 4, respectively. The intersection capacity utilization (ICU) was used to quantify the degree of congestion at intersections [52]. The reported data include the ICU and the maximum volume-to-capacity ratio ($Max\frac{v}{c}$) for the critical intersection on the coordinated path (Table 3).

Table 2. Initial Turn Movement Count Used for the Case Study

Intersection		A	B	*C	D	E
Eastbound	L	-	201	115	817	-
	Th	932	705	789	-	532
	R	174	139	153	73	503
Westbound	L	98	127	123	-	133
	Th	309	258	234	-	531
	R	-	221	201	-	-
Northbound	L	117	81	206	198	286
	Th	-	202	446	393	-
	R	91	166	17	-	922
Southbound	L	-	210	78	-	-
	Th	-	252	614	270	-
	R	-	68	152	347	-

* Unsignalized Roundabout; ** L: Left, Th: Through, R :Right.

Table 3. Impact of the proposed method on delays across various ICUs

Scenarios	ICU	Max v/c	Vehicle Delay (Sec.)		P-value
			Base Case*	Proposed Method (% Change)	
1	0.5	0.6	61	-5%	< 0.001
2	0.6	0.7	69	-7%	< 0.001
3	0.75	0.95	112	-14%	< 0.001
4	0.8	1.1	166	-17%	< 0.001

* Conventional Traffic Signal Coordination

The selected test site for this detailed simulation was a 9-mile section of King Khaled St. in Medina, KSA, stretching between Pr. Naif Rd. and AsSih Dr. (Figure 4). This section contained 2–3 lanes in each direction, a median left-turn lane, four intersections, and a roundabout at its midpoint, with a speed limit of 80 km/h. The simulated network was deliberately chosen for its diverse mix of intersections and roundabouts, offering a comprehensive representation of typical urban traffic scenarios.

5. Results and Discussion

The proposed method was evaluated using ten randomized runs for each scenario, with unique random seed values to ensure robust results. Each scenario was simulated for one hour after a warm-up period of 1,000 s to stabilize the model.

The delay results, summarized in Table 3, demonstrate a notable reduction in vehicle delays along the coordinated arterial across various ICU levels. The reductions ranged from 5% at an ICU of 0.5 to 17% at an ICU of 0.8. Additionally, the table highlights the average delays for each scenario, the percentage improvements achieved by the proposed method, and the corresponding p-values. The fact that the results were statistically significant ($p < 0.01$) in all scenarios confirms the reliability and robustness of the findings, ensuring that the observed reductions are not due to random variations.

Stop delays were also improved, with reductions ranging from 3.5 to 26 seconds depending on the ICU level (Figure 5). At an ICU of 0.5, an 11% reduction was achieved, representing notable efficiency gains. The proposed method yielded even higher improvements at elevated ICU levels, with reductions of 15%, 24%, and 28% at ICU levels of 0.6, 0.75, and 0.8, respectively. The p-values (all < 0.01) for these reductions confirm that the improvements are statistically significant, underscoring the reliability of the method in minimizing stop delays. The peak improvement of 28% at ICU 0.8 underscores the capability of the method to optimize signal timing under high-demand conditions. These reductions translate into shorter waiting times for drivers and enhanced traffic flow, demonstrating the effectiveness of the approach in mitigating congestion.

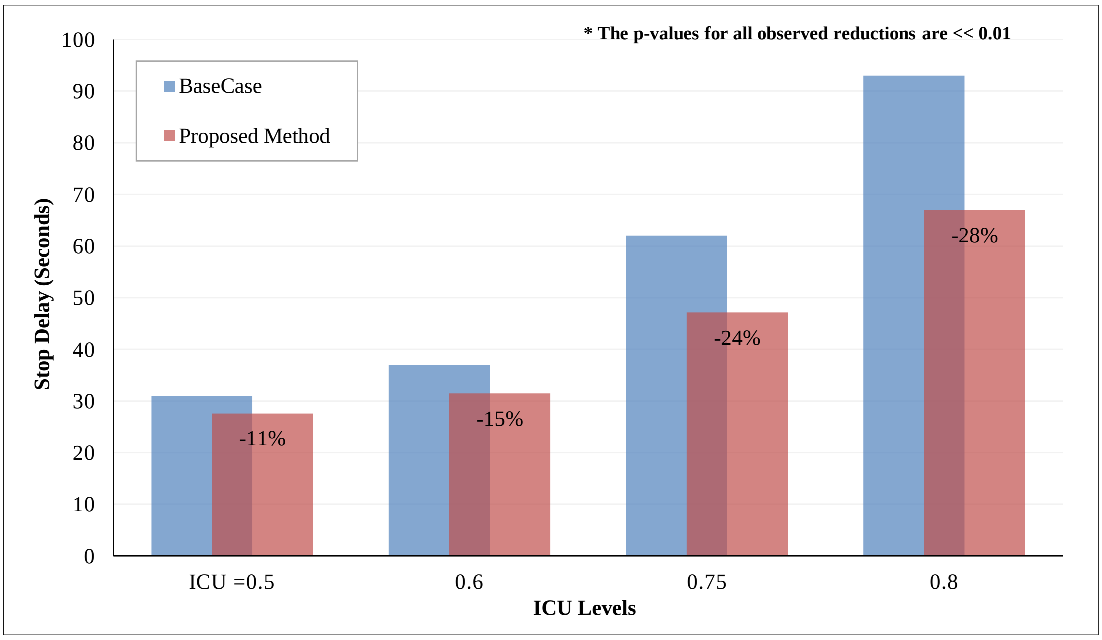

Figure 5. Comparison of stop delay reduction between the base case and proposed method at various ICU levels

In addition to improving traffic flow, the method significantly reduces fuel consumption and emissions of key pollutants, including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and carbon dioxide (CO_2), as indicated in Table 4. These reductions become increasingly pronounced at higher ICU levels, with CO and CO_2 emissions decreasing by 11% and 16%, respectively, at an ICU of 0.8. The statistical significance of these environmental improvements, indicated by p-values below 0.01, highlights the reliability of the observed trends. This trend highlights the efficiency of the proposed method in addressing environmental challenges associated with urban congestion. By lowering fuel consumption and emissions, the method contributes to sustainability goals, improved air quality, and enhanced urban livability.

Table 4. Impact of the proposed method on pollutant reduction and fuel efficiency under various ICUs

	CO	HC	NO_x	Fuel	CO_2
ICU = 0.50	-2%	-1%	-1%	-3%	-3%
ICU = 0.60	-3%	-2%	-1%	-5%	-5%
ICU = 0.75	-8%	-6%	-6%	-12%	-12%
ICU = 0.80	-11%	-9%	-9%	-16%	-16%

* Note: All p-values are <0.01.

The results align with those of prior studies that emphasize the benefits of well-coordinated traffic systems, particularly under high-demand scenarios. The proposed method's observed effectiveness in reducing delays and emissions is attributed to enhanced vehicle platooning. However, a lack of existing literature on integrating traffic light coordination with intercalated roundabouts limits direct comparisons, highlighting the innovative nature of the proposed approach.

These findings underscore the potential of the proposed method to transform urban traffic management through a dual focus on operational efficiency and environmental sustainability. The significant reductions in delays and emissions, validated by statistically significant p-values, indicate the ability of the method to enhance traffic flow, reduce economic and social costs of congestion, and contribute toward global sustainability goals.

6. Conclusion

This study addresses the existing knowledge gap about coordinated multi-intersections with a roundabout in the middle. The study proposed a framework that enhances the rules of coordination, including an adaptive offset with a platoon compaction factor to consider for platoon dispersion in roundabouts. The performance of the proposed method was evaluated using microsimulation tests on a network with four intersections and a roundabout. A case study was conducted on King Khaled Street in Medina, Saudi Arabia, where the intersections were irregularly spaced. The proposed system was evaluated using the coordinated-actuated control of arterials as a benchmark.

The proposed method outperformed traditional coordinated signal control, particularly in terms of efficiency and environmental impact. The key metrics showed substantial improvements across different levels of congestion. In particular, the overall average delay and the average delay per stop showed maximum reductions of 16% and 28%, respectively. The environmental impact analysis produced promising results, showing significant reductions in emissions: up to 16% for CO_2 , 11% for CO, and 9% for NO_x.

These findings highlight the potential advantages of implementing the proposed framework in real-world traffic management scenarios, particularly in locations with characteristics similar to King Khaled Street in Medina. By reducing congestion and enhancing air quality, this study contributes to the development of highly efficient and eco-friendly urban transportation systems.

Future research should include additional case studies that explore a broader range of geometric variables to provide a more comprehensive understanding of the effectiveness of the algorithm across diverse traffic scenarios. Moreover, developing a technique that integrates the algorithm with existing traffic management systems can enhance its practical utility and efficiency in real-world applications.

7. Declarations

7.1. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.2. Funding

The author received no financial support for the research, authorship, and/or publication of this article.

7.3. Conflicts of Interest

The author declares no conflict of interest.

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