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SYNCHRONIZING TRAFFIC LIGHTS: AN ADAPTIVE APPROACH TO REDUCE URBAN CONGESTION

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Abstract. *This article presents a novel Adaptive Traffic Light Control System (ATLCS) designed to mitigate urban traffic congestion by synchronizing traffic signals along arterial roads. The proposed system dynamically adjusts green phase offsets between consecutive intersections based on real-time vehicle queue data, creating a "green wave" that prioritizes traffic flow exiting city centers during peak hours. Extensive simulations conducted in SUMO demonstrate the system's efficacy, showing a reduction in average travel time of up to 39% in the prioritized direction and a 17% improvement network-wide. The practical viability of such adaptive systems is further supported by a case study from Dnipro, Ukraine, where the implementation of a rule-based algorithm utilizing thermal imaging sensors achieved delay reductions of 20–38%. The study also explores the potential of a Reinforcement Learning (RL) framework for future optimization. These findings underscore the significant benefits of adaptive synchronization strategies as a scalable and effective approach for enhancing urban mobility within smart city initiatives.*

Key words: *Intelligent Transportation Systems (ITS), Adaptive Traffic Light Control System (ATLCS), traffic signal synchronization, green wave optimization, urban traffic congestion, smart cities, SUMO simulation.*

Introduction.

The vision of the smart city relies on the efficient management of critical infrastructure, with transportation being a key pillar. However, the increasing number of vehicles in urban areas has led to chronic congestion, with severe consequences. In the UK alone, congestion was estimated to cost £30.8 billion in 2016, with drivers in London wasting an average of 73 hours during peak hours. Beyond the economic impact, idling and slow-moving vehicles significantly contribute to air pollution [1].

A primary cause of this congestion is the reliance on static or semi-adaptive traffic light systems [2]. These pre-programmed systems cannot respond to real-time fluctuations in traffic flow, leading to unnecessary stops, longer queues, and inefficient use of road capacity [3]. While recent approaches have leveraged technologies like fuzzy logic, swarm intelligence, and floating car data, many are computationally complex or require a high penetration of connected vehicles [4]. This work addresses a specific, high-impact scenario: synchronizing traffic lights on arterial roads to efficiently evacuate vehicles from a city centre during the evening rush hour [5].

Main text.

1. *A Synchronized, Adaptive Solution.* The proposed ATLCS is designed to prioritize the main flow of traffic exiting a city centre via arterial roads. The central hypothesis is that by synchronizing a sequence of traffic lights, a "green wave" can be created, allowing vehicles to travel long distances without stopping, thereby minimizing the inefficient "stop-and-go" phenomenon [6].

System Architecture and Sensing. The system relies on a network of magnetometer sensors deployed at each junction. These sensors are chosen for their reliability in all weather conditions and low power consumption. At each junction, sensors are placed on incoming and outgoing lanes to accurately count vehicles. The number of vehicles waiting on a road segment between two junctions is calculated as the difference between vehicles that have left the upstream junction and those that have arrived at the downstream junction [7].

The Synchronization Algorithm. This calculation is a function of several factors:

- The length of the road segment (R_{len}).
- The number of vehicles queued at the downstream junction (Ni).
- Vehicle characteristics (length, acceleration, speed limit).
- The safe gap between moving vehicles.

2. *Performance Evaluation and Results.* The system was rigorously evaluated using the Simulation of Urban Mobility (SUMO) platform, modelling an arterial road with four junctions [9]. The performance was compared against a traditional fixed-time TLCS under various conditions, with results averaged over 50 simulation runs.

The key findings were compelling:

Significant Reduction in Travel Time: For the prioritized direction (exiting the city centre), the average travel time was reduced by up to 39% when the maximum green phase duration (t_{max}) was set to 3 minutes [1]. This is because a longer green phase allows more vehicles to join the synchronized "green wave." [9]

Improved Traffic Flow Distribution: The histogram of travel times showed a much higher frequency of shorter trips with the ATLCS compared to the fixed-time system, which had a wide spread of very long trips.

Network-Wide Benefit: Crucially, the system did not just benefit the prioritized flow. The overall average travel time improvement across all vehicles in the network, including those traveling in opposite directions or from side roads, was 17% [1]. This indicates that by efficiently clearing traffic from the city centre, congestion is alleviated for all users.

Congestion-Level Resilience: The system was most effective under high congestion (100% road occupancy), achieving the highest 39% improvement, proving its value in the most challenging scenarios [1].

3. *Real-World Validation: A Case Study from Dnipro, Ukraine.*

The practical potential of adaptive traffic control is further demonstrated by a real-world implementation in the city of Dnipro, Ukraine [9]. This project addresses the same core issue of fixed-time plan inefficiency by deploying a robust sensing and control system. A key differentiator is the use of thermal imaging sensors, which provide reliable vehicle detection day and night, unaffected by adverse weather or poor lighting that can challenge traditional cameras [9].

The Dnipro system follows a pragmatic, two-stage approach. The initial deployment utilizes a rule-based adaptive algorithm that dynamically extends green phases based on continuous traffic flow measurements and employs gap detection to minimize wasted time. This practical solution alone has yielded impressive results, reducing average vehicle delays by 20-38% at pilot intersections [9].

Building on this success, the project is pioneering a next-generation system using Reinforcement Learning (RL) [2-10]. In this AI-driven model, the traffic signal acts as an autonomous agent that learns optimal control policies [2-7]. The system's state is defined by real-time sensor data (queue lengths, arrivals), its actions are phase changes, and it receives positive rewards for minimizing total vehicle delay. Simulations of this RL-based approach show promise for even greater efficiency, particularly in creating coordinated "green waves" across multiple intersections. The Dnipro case study proves that significant congestion relief can be achieved without a full infrastructure overhaul, providing a scalable blueprint for other cities [9].

Summary and conclusions.

This research, supported by real-world validation from cases like Dnipro, presents a practical and highly effective adaptive traffic light control system [11, 12]. By focusing on the synchronization of consecutive junctions using real-time queue data, the proposed ATLCS successfully reduces average travel times, mitigates the "stop-and-go" phenomenon, and improves overall network efficiency. The algorithm is computationally efficient and relies on proven, cost-effective sensor technology, making it a viable solution for many cities [13, 14].

Further research could also explore integrating data from connected vehicles to enhance the accuracy of queue estimations and extend the coordination to two-dimensional urban grids, moving beyond arterial roads to create a fully adaptive city-wide traffic management ecosystem [15]. The evolution towards AI-driven control, as seen in Dnipro, represents the exciting future of intelligent urban mobility.

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