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Practical Applications and Systemic Bottlenecks of Intelligent Transportation Systems in Urban Traffic Management: A Case-Based Analysis

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Abstract. The sharp increase in urban vehicle ownership has triggered severe traffic congestion and low road network operational efficiency, making intelligent transportation systems (ITS) a core technical means to optimize urban traffic management. Nevertheless, existing studies have obvious deficiencies: there is a lack of systematic collation and comparative analysis of ITS practical applications across diverse urban scenarios, and the exploration of developmental constraints is fragmented without integrating inherent correlations among industrial standards, equipment compatibility and operational costs. This paper adopts literature research, case analysis and inductive methods to select typical urban cases in Indonesia, Poland and Malaysia, exploring the practical effects of ITS on signal timing optimization, short-term traffic flow prediction and multi-intersection collaborative control under traffic disturbances. The results indicate that simulation modeling, regression algorithms and deep reinforcement learning can effectively reduce traffic queue length and travel delay, and improve traffic prediction accuracy and road network operation efficiency. This study further identifies three systemic bottlenecks restricting ITS large-scale promotion: poor adaptability to extreme weather and unexpected traffic incidents, insufficient standardization and scalability for city-wide deployment, as well as data privacy risks and user psychological resistance. It also clarifies research limitations and proposes future research directions, aiming to provide theoretical support and practical references for urban intelligent traffic governance and bottleneck breakthroughs.

Keywords: Intelligent transportation systems, Urban traffic management, systemic bottlenecks

1. Introduction

The rapid growth of urban vehicle ownership has caused several problems, such as traffic congestion, and low road network efficiency. However, with the development of some core technologies, the intelligent transportation system (ITS) has become a possible efficient management solution for regulating urban traffic flow. While current research has made great progress in traffic flow prediction, intelligent signal control and vehicle-road collaboration, with

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relevant models and technologies piloted in many cities, there are obvious gaps in the existing research: a lack of systematic review of ITS practice cases in different urban scenarios and the analysis of development bottlenecks, such as inconsistent industry standards, insufficient hardware and software compatibility, and high operation and maintenance costs are relatively scattered.

This paper focuses on the practical cases and development bottlenecks of ITS in urban traffic flow regulation. Adopting literature research, case analysis and induction methods, it explores the application models, effects and obstacles of ITS. The study aims to sort out practical experience, identify key bottlenecks, predict that ITS will develop toward integrated collaboration, standardized popularization and low-cost deployment, and provide theoretical support and practical suggestions for urban intelligent traffic regulation.

2. Literature review and conceptual differentiation

2.1. Core concepts of ITS and related management strategies

ITS is a system that covers a broad range of communication, control, vehicle sensing and electronics technologies to improve safety, mobility and efficiency [1]. By integrating multiple technologies, ITS enables cities to automatically adjust traffic light durations and timing schemes based on real-time traffic flow, and to rapidly detect abnormal conditions such as traffic accidents and road construction through video analytics and sensors.

Transportation system management (TSM) and transportation demand management (TDM) are two transportation management strategies that emerged in 1970s. The core difference between these two strategies is that TDM aims to guide people to adopt scientific traffic behaviors, like increasing the attractiveness of public transport through directly reducing bus and subway fares, while TSM still focuses on coordinating each of the parts in the urban transportation system to achieve the maximum profits rather than restricting the demands [2].

ITS, TDM and TSM are distinct yet interconnected pillars of modern urban traffic governance. As a technology-enabled governance paradigm, ITS empowers both TDM and TSM. It leverages IoT, big data and AI to achieve full-spatiotemporal traffic perception, data-driven decision-making, proactive congestion prevention and cross-modal coordination, breaking the limitations of traditional experience-based management and realizing dynamic matching between traffic supply and demand.

2.2. Gaps in existing research

Rome comes up with a new real-time monitoring through cell phones, as traditional ITS relies on fixed sensors and GPS receivers to collect traffic data and these two pieces of equipment have several problems during the implementation [3]. One of the major intersections at Rzeszów uses a new model called trigonometric regression to reduce traffic congestion. However, none of these studies have a systematic summary of ITS cases on a large scale.

Sustainable traffic management in smart cities has not been fully studied due to system complexity and traffic flow heterogeneity, and there is a technical gap in the implementation of the integration of the Internet of Things (IoT) and Intelligent Transportation Systems (ITS) [4]. Malaysia identifies 6 major dimensions, including technical, resources, interoperability, management, economic and individual, with 20 core challenges in the whole process of the ITS [5]. However, the multi-dimensional challenge framework proposed by Malaysia only provides a macroscopic classification without forming targeted solutions for practical bottlenecks. Most

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existing studies analyze technical defects, economic burdens and management issues in isolation, failing to correlate scattered bottleneck factors and explore the internal correlation between standardization construction, equipment compatibility optimization and cost control.

3. Case studies: ITS applications in diverse urban contexts

3.1. Indonesia: signal light controlling

The Haji Bau-Cendrawasih-Arif Rate intersection in Makassar, Indonesia, is located in the commercial core area. During peak hours, traffic volume is high, with prominent queuing and delay issues. However, as the road infrastructure cannot be expanded, the optimization of signal control is a low-cost, easily implementable congestion-mitigation solution in this city.

A micro-traffic simulation approach was applied using PTV Vissim software. The model adopted the Wiedemann 74 car-following model for urban driving behavior, calibrated via trial-and-error parameter adjustment. It was validated by the GEH test (for traffic volume) and chi-square test (for queue length), with all values meeting accuracy standards.

There are two signal timing schemes being tested. Scheme 1 shortened the cycle from 84s to 60s while keeping 2-phase control; Scheme 2 used a 60s 3-phase design with a 10-second late start for the Cendrawasih approach to reduce traffic conflicts.

Finally, scheme 2 delivered the best performance, reducing queue length by up to 76% and delay by up to 51%. This case proves micro-traffic simulation is a reliable tool for signal control optimization, effectively easing urban intersection congestion with low-cost improvements [6].

3.2. Rzeszów

Rzeszów is a representative smart city with a complete real-time traffic data collection and processing system. With rapid urbanization and rising vehicle ownership, the city faces severe traffic congestion at core intersections. Such congestion reduces travel efficiency, disrupts public transport regularity and increases operation costs, making accurate short-term traffic prediction critical for intelligent traffic control. The study uses hourly traffic data collected on July 12, 2022, at the busy intersection of Powstańców Warszawy Avenue and Batalionów Chłopskich Avenue, covering 10 key road connections (Figure 1).

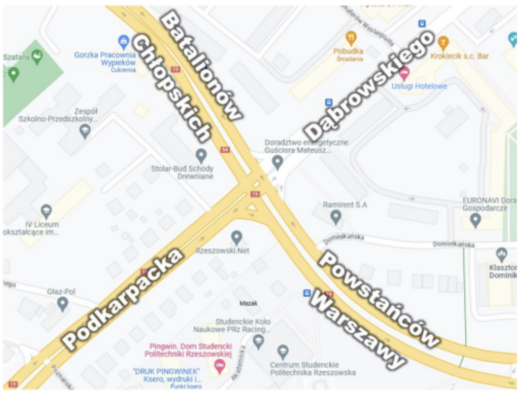

Figure 1. The map of the Powstańców Warszawy Avenue and Batalionów Chłopskich intersection [7]

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There are thirteen generations of regression models being tested, including linear, polynomial, trigonometric, polynomial-trigonometric models and the Random Forest algorithm. All these models were evaluated through multiple R, R^2, adjusted R^2 and standard error. During the evaluation, polynomial models suffered from serious overfitting with extremely high errors, while the Random Forest algorithm performed worse than linear regression.

After iterative optimization, the pure trigonometric model achieved the best performance. It reached multiple R=0.980, R^2=0.961, adjusted R^2=0.922 and standard error=29.320. After normalization, the model delivered an average R^2 of 0.982 across all connections and supported minute-level traffic prediction.

This trigonometric regression model is well-suited for Rzeszów's city traffic supervision systems. The study recommends extending the data timeline and exploring Chebyshev polynomial models to further enhance practical real-world deployment [7].

3.3. Sunway City

Sunway City is a vibrant urban hub in Malaysia with dense residential communities, commercial districts, several universities and medical center. However, this led to severe peak-hour traffic congestion. Malaysia has heavy annual rainfall and frequent thunderstorms, which serve as typical traffic disturbances that worsen congestion. This real-world scenario with high traffic volume and frequent disturbances makes it an ideal case to validate adaptive traffic signal control strategies (Figure 2).

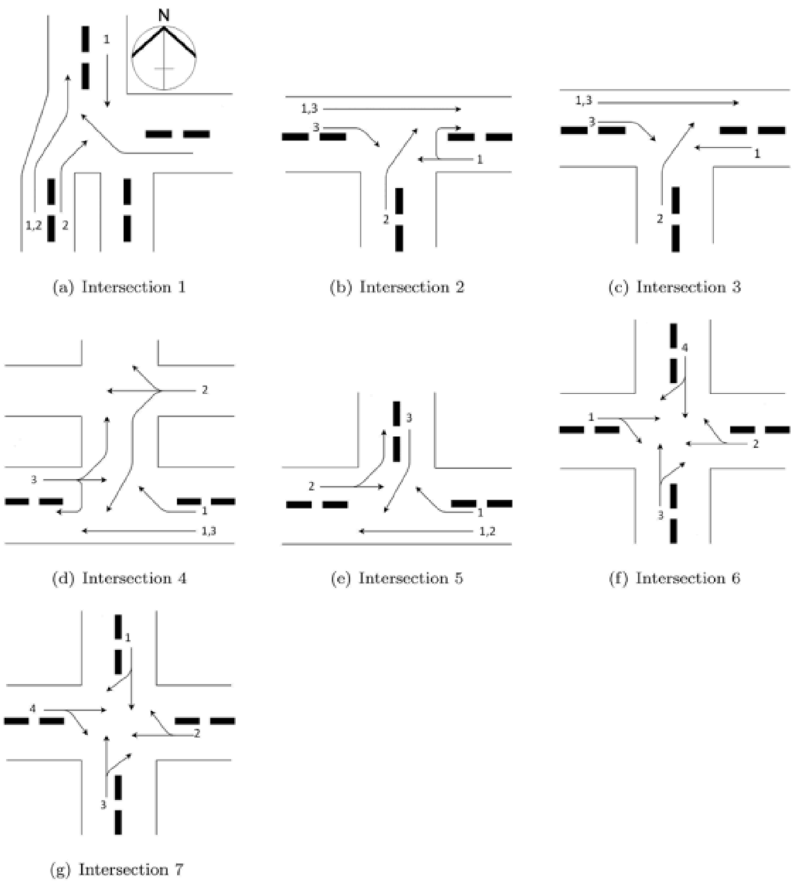

Figure 2. A series of traffic phases of a traffic signal controller at an intersection [8]

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The researchers develop a Multi-Agent Deep Q-Network (MADQN), which combines deep reinforcement learning's (DRL) neural network representation and Multi-Agent Reinforcement Learning's (MARL) collaborative decision-making ability to address traffic congestion under disturbances, using the Burr type XII distribution to model vehicle arrival patterns (replacing the traditional Poisson process) to fit rainfall-impacted traffic flow. Simulations are carried out via SUMO and MATLAB on 7 real intersections in Sunway City and a 3×3 grid network, compared with deterministic control, RL and MARL.

According to the research results, MADQN significantly optimizes traffic performance in the sample: it raises throughput by up to 70%, cuts queue length by 75% and reduces waiting time by 70%. With experience replay and a target network, MADQN achieves more stable training, solves the curse of dimensionality and realizes collaborative multi-intersection signal control, providing a feasible solution for disturbance-prone urban traffic management [8].

4. Systematic bottleneck analysis

4.1. Limited adaptability to dynamic and unforeseen conditions

Abrupt traffic disturbances such as extreme weather and unexpected incidents are hard to quantify during the simulation process. A study conducted in 2020 mentioned that non-recurrent disturbances like heavy rainfall fundamentally reshape vehicle arrival patterns and flow distribution [1]. Conventional ITS systems are designed and optimized only for regular, recurring congestion, which means that they lack proactive sensing, identification, or adaptive response mechanisms for such sudden changes. Traditional traffic models have no ability to capture the distorted flow characteristics under disturbances. Once a disturbance occurs, the whole control system becomes unresponsive and cannot adjust works like signal timing, traffic guidance strategies, or prediction models in real time. Therefore, the system cannot deal with sudden congestion caused by external shocks and may even worsen queue length and vehicle delay. This structural limitation means ITS remain reliable only under stable traffic conditions and lose effectiveness in complex, dynamic urban environments, greatly restricting their practical value and robustness.

4.2. Scalability and standardization challenges in large-scale deployment

Some of the existing models and optimization methods are designed and validated for individual intersections, making them difficult to replicate across an entire urban road network because of each network's uniqueness. As shown in Dymora, P., Mazurek, M. & Jucha, M. [7], regression-based traffic prediction models require separate coefficient training and fine-tuning for each road connection. There is no doubt that this customized, case-by-case configuration will lead to extremely low efficiency and high implementation costs when extended to a city-wide system. Without unified modeling standards and standardized deployment processes, it is hard for transportation authorities to rapidly roll out ITS solutions across multiple intersections or regions. In addition, the lack of scalability leads to inconsistent performance, poor compatibility between subsystems, and increased maintenance complexity. Such limitations prevent ITS from moving beyond pilot projects to full-scale urban applications, significantly restricting its practical value and real-world impact.

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4.3. Privacy and security concerns impeding user acceptance

Privacy risk has emerged as a dual-dimensional critical bottleneck, severely impeding the widespread adoption and large-scale application of ITS. It encompasses both technical data security vulnerabilities and user psychological trust deficits, and the interaction between these two dimensions creates an inherent contradiction between the technical advantages of ITS and user acceptance. From the technical dimension, ITS requires the extensive collection of highly sensitive data, including vehicle trajectories, personalized driving behaviors and user identity information, to support core functions ranging from real-time traffic status monitoring to accurate vehicle tracking. The immature and incomplete supporting mechanisms concerning data encryption, information anonymization and hierarchical access control leave collected sensitive data vulnerable to leakage, illegal access and improper abuse [9], posing direct threats to users' personal information security. From the psychological dimension, underlying privacy risks trigger widespread privacy anxiety and explicit psychological resistance among end users. The invisible long-term data monitoring mechanism makes users worry about the loss of control over personal private information, generates the perceived sense of being spied on, and ultimately undermines users' subjective trust in intelligent transportation systems.

In Tanzania, there are 207 male truck drivers with an average driving age of 10.7 years being tested about the view of the ITS through a questionnaire. Although most of them generally recognize the value of ITS in reducing traffic accidents, such as collisions and easing congestion, they hold a negative attitude towards telematics (vehicle tracking system) due to clear privacy concerns [10]. This reflects that the privacy anxiety of end-users has become a practical obstacle to ITS adoption. In regions with imperfect regulatory systems, such as Tanzania, the absence of targeted privacy protection policies and transparent data management mechanisms further amplifies this bottleneck, resulting in the contradiction between the technical advantages of ITS and user trust, restricting its large-scale landing and stable operation.

5. Conclusion

This paper systematically explores the practical applications and inherent systemic bottlenecks of Intelligent Transportation Systems (ITS) in urban traffic management through literature review, comparative case analysis and inductive reasoning. It first clarifies the connotation of ITS and its logical correlation with TSM and TDM, and identifies two prominent research gaps in existing studies: the lack of systematic large-scale collation of practical ITS cases and the scattered and isolated analysis of ITS development constraints. To fill these research gaps, this paper selects three typical cases covering Indonesia, Poland and Malaysia to investigate the application effects of ITS on signal timing optimization, short-term traffic flow prediction and multi-intersection collaborative control under traffic disturbances, respectively. The case results verify that simulation modeling, regression algorithms and deep reinforcement learning can effectively alleviate intersection congestion, improve traffic prediction accuracy and optimize network-wide traffic operation efficiency. Furthermore, this paper summarizes three core bottlenecks restricting the popularization and deployment of ITS: poor adaptability to dynamic unforeseen traffic disturbances, such as extreme weather, insufficient standardization and scalability for city-wide large-scale promotion, and dual privacy risks stemming from technical data security loopholes and users' psychological trust deficiency. The findings well answer the research questions proposed in the introduction and reveal the fundamental contradiction between the technical advantages of ITS and its practical large-scale implementation.

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Despite the above findings, this study still has certain limitations. First, the selected empirical cases are only concentrated in several Southeast Asian and Eastern European cities, without involving developed Western cities and Chinese urban scenarios, which limits the generalizability of the research conclusions. Second, the analysis is mainly based on existing literature and secondary data from previous studies, without combining field investigation, original questionnaire research and measured traffic data, resulting in insufficient empirical depth of the research.

In view of the above deficiencies, future research can be expanded in two main directions. Firstly, more diversified case samples covering Chinese cities, Western developed regions and other developing countries should be included to conduct cross-regional comparative analysis, to summarize more universal application rules and bottleneck characteristics of ITS. Secondly, follow-up research can adopt field interviews, questionnaire surveys and real-time traffic data collection to obtain first-hand empirical data; quantitatively evaluate the impact of environmental disturbance, industry standardization and privacy concerns on ITS adoption; and further propose targeted and operable optimization strategies for breaking through the existing systemic bottlenecks of urban ITS.

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