Journal of Sustainable Build Environment

https://doi.org/10.70731/agvc2744

A Framework for Promoting IoT- and Digital Twin-Enabled Intelligent Traffic Light Systems in China: an Empirical Study Based on a Malaysian Smart City Facilities Management Case

Qi Wu [a,*], Bowen Lu [a], Junda Pan [a]

[a] Faculty of Built Environment, University of Malaya, Kuala Lumpur, Malaysia,50603

KEYWORDS

Intelligent Traffic Light Systems,
Internet of Things,
Digital Twins,
Smart Cities,
Sustainable Urban Development,
Traffic Optimization,
Environmental Sustainability,
Urban Infrastructure Management.

ABSTRACT

This study explores the potential for the implementation of an advanced Intelligent Traffic Light System (ITLS) in Chinese urban landscapes, integrating Internet of Things (IoT) and digital twin technologies for sustainable urban development. Using empirical data from the Malaysia Smart Traffic Light Management (MSTLM) program, we assessed the effectiveness of the system on multiple dimensions critical to sustainability. Statistical analysis of eight cities showed significant improvements in vehicle safety programs: average travel time was reduced by 37.7%, congestion index by 38.5%, fuel consumption by 27.3%, and CO_2 emissions by 18.4%. In addition, system reliability was significantly improved with 98.3% uptime and 280.5% increase in signal conditioning frequency. The study presents a comprehensive framework tailored to China's urban environment, emphasizing technical architectures, deployment strategies, and policy recommendations aligned with the SDGs. Our findings contribute to the debate on smart city infrastructure management, providing actionable insights for policymakers, urban planners, and stakeholders committed to resilient and sustainable urban growth providing an adaptable roadmap for large-scale deployment in rapidly urbanizing Chinese cities. Our findings bridge Malaysian empirical insights to China’s distinct infrastructure and governance structures.

1. Introduction

1.1. Background and Motivation

In recent decades, China's rapid urbanization has fostered unprecedented growth in metropolitan areas, leading to significant advances in infrastructure, economic development and technological innovation (Liu et al., 2024; Magazzino & Mele, 2021). However, this exponential urban expansion has triggered multifaceted challenges, especially in the area of urban traffic management. Growing car ownership exacerbates traffic congestion, leading to longer travel times, increased fuel consumption, higher CO2 emis-

* Corresponding author. E-mail address: wuqi7728@gmail.com

Received 21 December 2024; Received in revised form 2 January 2025; Accepted 10 January 2025; Available online 31 January 2025.
2759-7318 /

sions and significant economic losses (Leroutier & Quirion, 2023).

Traditional traffic management systems, which rely mainly on static signal timing and manual intervention, are increasingly unable to cope with the dynamic complexity of modern urban traffic. The management of transportation infrastructure facilities also presents obvious challenges. The proliferation of traffic monitoring equipment, signal control systems, and supporting infrastructure requires complex facilities management practices (Li et al., 2022). Traditional facility management practices often struggle to maintain optimal performance of these systems, resulting in increased maintenance costs and reduced system reliability. Modern traffic management facilities require intelligent monitoring systems and predictive maintenance protocols to ensure continuous operations and maximize the useful life of the infrastructure. However, existing literature seldom addresses how IoT and digital twin-based traffic systems, proven effective in smaller-scale pilot projects or developed regions, can be adapted to rapidly urbanizing environments with substantial infrastructural variations—a key gap this study aims to fill.

At the same time, the pressing global need for sustainability shows that innovative solutions must be employed to mitigate environmental impacts while improving the livability of cities (Bibri & Krogstie, 2020; Wu, 2023). The integration of cutting-edge technologies such as the Internet of Things (IoT) and digital twins offers transformative opportunities for positive change in transportation management. The IoT can facilitate real-time data collection and communication between interconnected devices, allowing for adaptive and intelligent control mechanisms (Khan et al., 2023). On the other hand, digital twin technologies can provide a virtual copy of the physical transportation system, granting the possibility of comprehensive simulation and predictive analysis (Qian et al., 2022). The convergence of these technologies in Intelligent Traffic Light Systems (ITLS) is not only expected to optimize traffic flow and reduce congestion, but also contribute significantly to environmental sustainability and economic efficiency.

The Malaysian Smart Traffic Light Management (MSTLM) project is a relevant empirical case study that demonstrates the tangible benefits of ITLS implementation. By analyzing data from eight major cities in Malaysia, this study attempts to extrapolate insights and develop a robust framework tailored for the Chinese urban environment. The overarching motivation is to leverage technological advances to promote sustainable urban development, improve the efficiency of traffic management, and align with the global Sustainable Development Goals (SDGs).

1.2. Research Objectives

This study is driven by a multifaceted set of objectives aimed at comprehensively evaluating and facilitating the adoption of ITLS in Chinese cities:

- **Evaluate the Effectiveness of IoT-Enabled Traffic Light Systems**: Through empirical analysis of operational data from the MSTLM project, assess the impact of ITLS on key performance indicators such as travel time efficiency, congestion indices, fuel consumption, and CO_2 emissions.
- **Develop an Implementation Framework for Chinese Urban Environments**: Formulate a comprehensive framework that addresses the unique technical, economic, and environmental contexts of Chinese cities, ensuring seamless integration and scalability of ITLS.
- **Assess Technical, Economic, and Environmental Impacts**: Conduct a holistic evaluation of ITLS implementation, encompassing technical architecture, cost-benefit analyses, and environmental sustainability metrics.
- **Propose Policy Recommendations for Large-Scale Deployment**: Formulate actionable policy guidelines that facilitate the widespread adoption of ITLS, fostering public-private partnerships, ensuring regulatory compliance, and promoting sustainable urban governance.

This leads to our core research question: Can IoT- and digital twin-enabled traffic light systems, validated in the Malaysian MSTLM project, produce significant sustainability gains in the complex urban environments of China?

1.3. Significance of the Study

As one of the most rapidly urbanizing countries in the world, China is at a critical juncture where the integration of MSTLM can have far-reaching impacts in terms of economic benefits, environmental sustainability and improved quality of urban life (Hui et al., 2023). By carefully analyzing the results of the MSTLM project, this study provides valuable empirical evidence to support the effectiveness of ITLS, thereby informing policy makers, urban planners, and stakeholders of the practical advantages and strategic considerations necessary for successful ITLS implementation.

In addition, a tailored implementation framework addresses the nuanced challenges inherent in large-scale urban deployments, such as infrastructure diversity, governance structures, and socioeconomic disparities. This study not only illustrates the technical and environmental advantages of ITLS, but also emphasizes the need to promote collaborative governance models and incentivize public-private partnerships to drive sustainable urban transformation. It is in line with the global sustainable development agenda to promote resilient and inclusive urban communities through the judicious application of advanced (Wu, 2024).

2. Literature Review

2.1. Evolution and Components of ITLS

ITLS represent a transformative evolution from traditional static traffic signal control to a dynamic, data-driven management framework. ITLS utilizes real-time data collection, processing, and adaptive control mechanisms to optimize traffic flow, reduce congestion, and enhance overall urban mobility (Elassy et al., 2024). ITLS deployments have been associated with significant improvements in travel time efficiency, fuel consumption, and emission reductions (Toulni et al., 2023).

The evolution of ITLS can be traced from basic traffic signals equipped with sensors to complex systems integrating advanced analytics and machine learning algorithms. The core components of an ITLS include traffic sensors (e.g., cameras, inductive loops), traffic control units (TCUs), IoT gateways, and communication networks (Rai et al., 2023). The integration of digital twin technology further enhances the ITLS by providing a virtual copy of the physical transportation system, facilitating simulation, predictive maintenance, and scenario analysis (Adel & HS Alani, 2024).

Empirical studies have consistently demonstrated the effectiveness of ITLS in alleviating traffic congestion, reducing travel time, and reducing greenhouse gas emissions (Kuang et al., 2019; J. A. Molina et al., 2020). For example, deployments in cities such as Singapore and Barcelona have significantly reduced peak hour travel times and fuel consumption (L. T. Molina et al., 2019; Savall-Mañó et al., 2024). However, challenges remain, including high initial deployment costs, interoperability issues with legacy systems, and concerns related to data privacy and security (Albouq et al., 2022).

2.2. IoT in Urban Traffic Management

IoT constitutes a network of interconnected devices capable of collecting, exchanging and analyzing data autonomously. In the context of urban traffic management, IoT facilitates real-time data acquisition from various sensors for dynamic traffic signal adjustments and informed decision making (Almutairi et al., 2024).

The IoT architecture for traffic management typically consists of a sensor layer, a communication layer, and an application layer (Rai et al., 2023). Protocols such as MQTT, CoAP, and Ethernet play a crucial role in ensuring efficient data transfer and interoperability between devices (Seoane et al., 2021). The emergence of 5G technology further enhances the capabilities of IoT for traffic management by providing high-speed, low-latency communications essential for real-time applications (Sefati & Halunga, 2023).

Many case studies highlight the successful integration of IoT in traffic management systems. In Türkiye, smart cities intelligent transportation systems project demonstrates the application of IoT in optimizing traffic flow and reducing congestion through real-time data analysis and adaptive control mechanisms (Gunes et al., 2021). Similarly, initiatives in European cities have achieved significant improvements in transportation efficiency and environmental sustainability through IoT-enabled ITLS deployments (Elassy et al., 2024).

Recent studies (Alfandi et al., 2021) stress the importance of data security and privacy in IoT-centric traffic systems. Particularly in large-scale Chinese cities, ensuring secure data streams and compliance with data governance policies is a critical success factor for widespread ITLS adoption.

2.3. Digital Twin Technology in Traffic Management

Digital twin technology involves creating virtual counterparts of physical systems for comprehensive monitoring, simulation and optimization (Botín-Sanabria et al., 2022; Javaid et al., 2023). In traffic management, digital twins help in visualization of traffic dynamics, predictive analytics and scenario testing to enhance the decision-making process (Ersan et

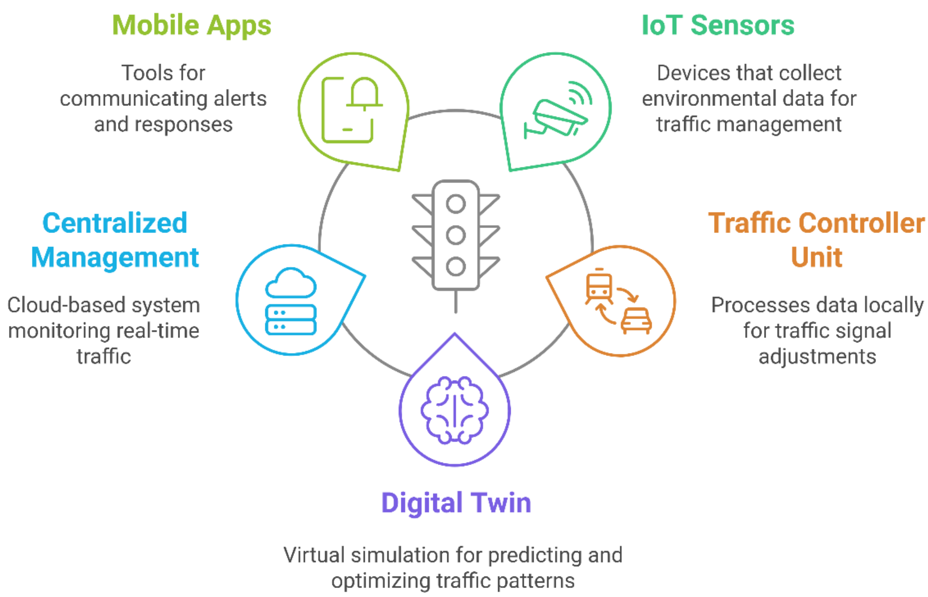

Figure 1 I Conceptual Framework

al., 2024). Digital twins typically involve the integration of real-time data streams with simulation models to create dynamic virtual environments that offer several advantages (Kušić et al., 2023), including enhanced predictive maintenance, improved traffic forecasting, and the ability to simulate the impact of infrastructure changes (Werbińska-Wojciechowska et al., 2024).

2.4. Sustainable Urban Development and Smart Cities

Sustainable urban development seeks to balance economic growth, environmental stewardship and social equity in urban settings (Kajiita & Kang'ethe, 2024). Smart cities, characterized by the integration of advanced technologies and data-driven governance, play a crucial role in achieving the sustainable development goals by improving the efficiency of urban services and infrastructure (Bibri, 2021). Intelligent traffic signal systems contribute to sustainable urban development by optimizing traffic flow, reducing vehicle emissions and improving the quality of urban life (Musa et al., 2023). By minimizing congestion and improving travel time efficiency, ITLS reduces fuel consumption and greenhouse gas emissions, thereby mitigating the environmental impact of urban transport (Elassy et al., 2024; Kuang et al., 2019). The effectiveness of ITLS is amplified when combined with other urban systems such as public transportation, emergency services and urban planning frameworks (Glazener et al., 2021).

2.5. Gaps in the Literature

Figure 1 conceptualizes the interdependencies between ITLS, IoT, and digital twin technologies, illustrating how real-time sensor inputs and predictive simulations converge to improve traffic management outcomes. This framework guides our empirical inquiries and informs the subsequent methodological design.

While substantial progress has been made in understanding the benefits and challenges of ITLS, some gaps remain. Notably, there is limited research on the contextual adaptation of ITLS to different urban environments, especially in rapidly urbanizing environments like China. Addressing these gaps is critical to developing comprehensive implementation frameworks that take into account the unique infrastructural, socioeconomic, and governance landscapes of different urban environments.

3. Methodology

3.1. Research Design

This study employs a quantitative research design, focusing exclusively on the analysis of empirical data from the MSTLM project. The objective is to evaluate the effectiveness of ITLS in improving urban traffic

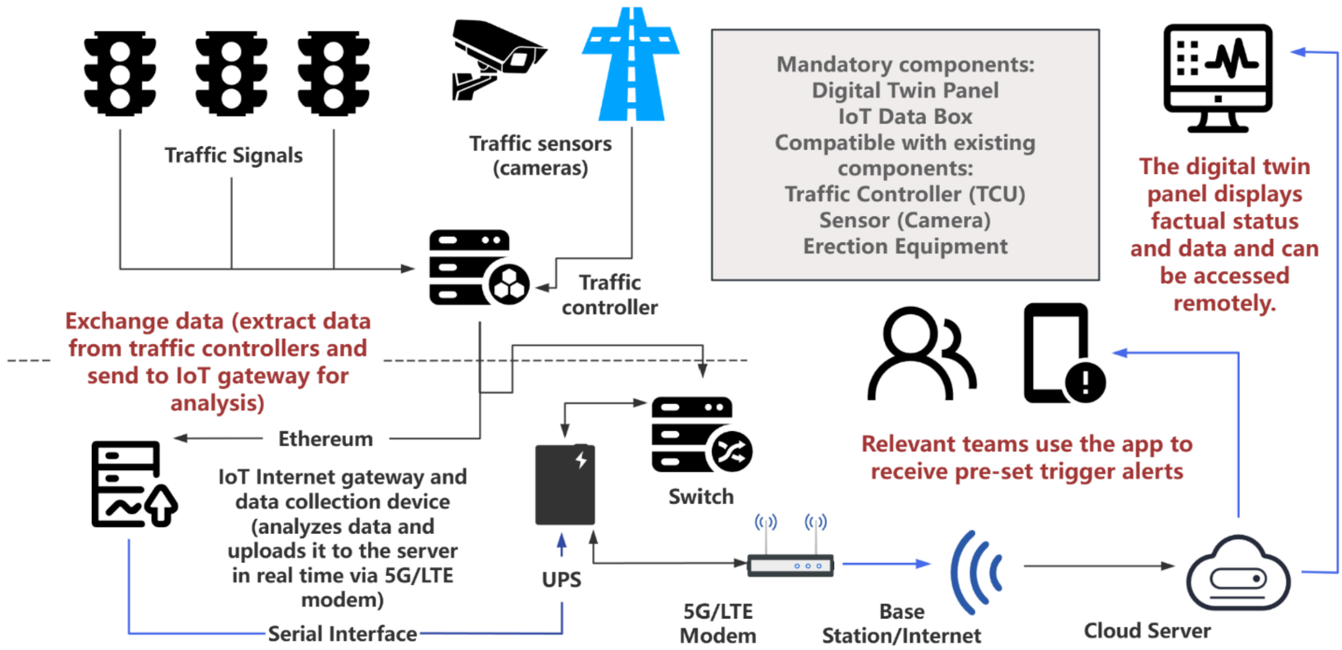

Figure 2 I MSTLM Technical Architecture Diagram

management and contributing to sustainable urban development. By leveraging statistical methods, the research aims to quantify the impact of ITLS across key performance indicators (KPIs) such as travel time efficiency, congestion index, fuel consumption, and CO_2 emissions.

3.2. Data Collection

Data for this study is sourced solely from the MSTLM project implemented in eight Malaysian cities. The data encompasses both pre-implementation and post-implementation metrics, providing a comprehensive basis for comparative analysis.The MSTLM dataset spans 12 months (from Feb 23 to Feb 24), capturing peak and off-peak traffic data in 30-minute intervals. Each city's dataset was consolidated into daily and weekly averages to align with the availability of maintenance logs and emission measurements.

The eight cities were selected based on (1) having established traffic sensor infrastructure, (2) government collaboration, and (3) diverse roadway characteristics (urban cores, suburban zones, etc.). This purposive selection provides a broad spectrum of traffic conditions while ensuring data comparability.

3.2.1. Operational Metrics:

- **Travel Time Efficiency**: Peak hour travel time measurements before and after ITLS implementation.
- **Congestion Index**: Real-time traffic flow data before and after ITLS implementation.
- **Fuel Consumption**: Daily fuel consumption rates before and after ITLS implementation.
- CO_2 Emissions: Daily CO_2 emission levels before and after ITLS implementation.

3.2.2. System Performance Metrics:

- System Uptime: Percentage of time the ITLS was operational.
- Daily Signal Adjustments: Number of daily adjustments made to traffic signals before and after ITLS implementation.

3.3. Data Analysis

The data collected was analyzed using robust statistical techniques to assess the impact of the ITLS on urban traffic management and sustainability indicators. The following methodology was used:

3.3.1. Descriptive Statistics

Descriptive statistics provide a basic understanding of the data by summarizing the central tendency, dispersion, and overall distribution of KPIs before and after the implementation of the ITLS.

- **Mean and Standard Deviation**: Calculate the average values and variability for each KPI across the eight cities.
- **Percentage Reduction/Improvement**: Determine the percentage change in each KPI post-implementation relative to pre-implementation values.

3.3.2. Paired t-Tests

A paired t-test was conducted to compare the means of the KPIs before and after ITLS implementation. This statistical test assesses whether the differences observed in the indicators are statistically significant. All t-tests were conducted in SPSS , and p-values are reported to three decimal places to ensure transparency.

3.3.2.1. Hypothesis Testing:

- **Null Hypothesis (H_1)**: There is no significant difference in the KPI before and after ITLS implementation.
- **Alternative Hypothesis (H_1)**: There is a significant difference in the KPI before and after ITLS implementation.

3.3.2.2. Significance Level:

A p-value of less than 0.05 is considered statistically significant.

3.4. Limitations

While the study provides valuable insights into the impact of ITLS, certain limitations must be acknowledged:

Table 1 I ITLS System Architecture Overview

Layer	Components	Description
Field Layer	• Traffic Signal Units • Traffic Sensors (Cameras) • Traffic Control Units (TCUs)	Core execution units managing vehicle flow, monitoring traffic conditions, and performing initial data processing.
Communication Layer	• Ethernet Protocol • Serial Interfaces • 5G/LTE Modems • Base Stations/Internet Connectivity	Facilitates data exchange, robust transmission, high-speed communication, and wide-area network support.
Processing Layer	• IoT Gateways and Data Acquisition Devices • Cloud Servers • Uninterruptible Power Supply (UPS) Systems • Switches	Handles real-time data analysis, extensive processing, power stability, and internal network communications.
Application Layer	• Digital Twin Panels • Mobile Applications • Remote Access Interfaces	Provides real-time visualization, remote monitoring, and centralized management capabilities.

Table 2 I ITLS Data Flow Processes

Process	Steps
Data Collection	1. Traffic signals and sensors capture real-time traffic data. 2. Traffic controllers process initial data locally. 3. IoT gateways aggregate and transmit data to cloud servers.
Data Processing	1. Real-time analysis by IoT gateways. 2. Data transmitted via 5G networks to cloud servers. 3. Cloud servers perform advanced analytics and store data. 4. Insights visualized on digital twin platforms.
Control Process	1. Decision-making on digital twin panels. 2. Instructions sent to cloud servers. 3. Cloud servers relay instructions to IoT gateways. 4. IoT gateways direct traffic controllers to execute signal adjustments.

- **Geographical Specificity**: The empirical data is exclusively from Malaysian cities, which may have different infrastructural and socio-economic contexts compared to Chinese cities.
- **Data Granularity**: Limited access to more granular data (e.g., minute-by-minute traffic flow) may constrain the depth of analysis.
- **Technological Variability**: Differences in ITLS technologies and implementation strategies across cities may introduce variability in the outcomes.

4. Results and Analysis

4.1. System Design and Implementation

ITLS implemented in the MSTLM project is based on a complex technological architecture integrating the IoT and digital twin technologies. Figure 2 in this section depicts the comprehensive system design, highlighting each architectural layer and its constituent components through structured Table 1 and Table 2 . In addition, it describes the system integration and data flow processes.

4.2. Empirical Data Analysis

The empirical analysis utilized quantitative data from the MSTLM program, focusing on eight major cities. The analysis assessed the impact of ITLS implementation on KPIs that are critical to sustainable urban development, including travel time efficiency, congestion index, fuel consumption, carbon dioxide emissions, system reliability, and frequency of signal adjustments.

4.2.1. Travel Time Efficiency

According to Table 3 ITLS implementation significantly reduced peak hour travel times in eight cities. Shah Alam City experienced the greatest improvement with a 45.0% reduction in travel time. On average, travel time decreased from 32.8 minutes to 20.4 minutes, a 37.7% reduction. A paired t-test confirmed the statistical significance of this reduction ($p= 0.003$).

(H_1: Average Peak Hour Travel Time Reduction: 37.7%)

4.2.2. Congestion Reduction

The congestion index, a key measure of traffic density and traffic efficiency, improved by an average of 38.5% after the implementation of ITLS as shown in Table 4. The pre-implementation average congestion index was 73.6%, which dropped to 45.3% after ITLS deployment. The city of Shah Alam City again showed the most significant decrease at 45.0%, while the other cities also showed significant improvements. A paired t-test confirms the statistical significance of these findings ($p = 0.002$).

(H_1: Average Congestion Index Improvement: 38.5%)

4.2.3. Fuel Consumption

As shown in Table 5, the deployment of the ITLS resulted in an average reduction of 27.3% in daily fuel

Table 3 | Travel Time Efficiency Before and After ITLS Implementation

City	Number of intersections	Percentage	Before implementation (minutes)	After implementation (minutes)	Reduction rate (%)
Kuala Lumpur	550	30.6%	45	28.5	36.7
Penang	320	17.8%	35	22.5	35.7
Johor Bahru	280	15.6%	38	24.5	35.5
Shah Alam	180	10.0%	32	19.7	38.5
Putrajaya	150	8.3%	25	16.0	36.0
Cyberjaya	120	6.7%	32	17.6	45.0
Kota Kinabalu	110	6.1%	28	17.5	37.5
Kuching	90	5.0%	27	17.2	36.3
Average	1,800	100%	32.8	20.4	37.7

consumption, which equates to a savings of approximately 1,390 liters of fuel per day per city. Shah Alam City reported the largest reduction of 45.0%, while the other cities reported reductions ranging from 23.5% to 25.5%. A paired t-test verified the statistical significance of these reductions ($p = 0.004$).

(H_1: Average Congestion Index Improvement: 38.5%)

4.2.4. CO_2 Emissions

The implementation of ITLS resulted in an average reduction of 18.4% in daily CO_2 emissions in the cities studied. Table 6 shows that the reductions ranged from 15.4% to 35.0%. The paired t-test confirmed the statistical significance of these reductions ($p = 0.008$).

(H_1: CO_2 Emissions Decrease: 18.4%)

4.2.5. System Reliability

ITLS has demonstrated excellent reliability, maintaining an average uptime of 98.3%. Monthly downtime has been reduced to an average of 12.4 hours, ensuring continued efficient traffic management. This high level of system reliability demonstrates the effectiveness of the robust architectural design and the redundancy and fail-safe mechanisms implemented.

4.2.6. Daily Signal Adjustments

With the implementation of ITLS, the frequency of daily signal adjustments increased dramatically from an average of 49.9 adjustments per day to 188.8 ad-

Table 4 I Congestion Index Before and After ITLS Implementation

City	Before implementation (minutes)	After implementation (minutes)	Reduction rate (%)
Kuala Lumpur	85.0	54.4	36.0
Penang	78.0	48.4	38.0
Johor Bahru	80.0	49.6	38.0
Shah Alam	72.0	44.3	38.5
Putrajaya	65.0	40.3	38.0
Cyberjaya	75.0	41.3	45.0
Kota Kinabalu	68.0	42.2	37.9
Kuching	66.0	41.6	37.0
Average	73.6	45.3	38.5

Table 5 I Fuel Consumption Before and After ITLS Implementation

City	Before implementation (liters/day)	After implementation (liters/day)	Reduction rate (%)
Kuala Lumpur	8,500	6,290	26.0
Penang	5,500	4,180	24.0
Johor Bahru	6,000	4,500	25.0
Shah Alam	4,800	3,576	25.5
Putrajaya	3,500	2,660	24.0
Cyberjaya	5,000	2,750	45.0
Kota Kinabalu	3,800	2,890	24.0
Kuching	3,700	2,830	23.5
Average	5,100	3,710	27.3

justments per day. This 280.5% increase reflects the system's increased ability to adapt to real-time traffic conditions, thereby optimizing traffic flow and reducing congestion.

4.3. Statistical Significance

Paired t-tests across all KPIs showed a statistically significant improvement after implementation of ITLS, with p-values well below the conventional threshold of 0.05. These results confirm that the observed reductions in travel time, congestion, fuel consumption, and CO_2 emissions, as well as improvements in system reliability and frequency of signal conditioning, are not due to random variations, but rather are important outcomes of ITLS implementation.

5. Discussion

5.1. Key Finding

The results presented in Chapter 4 highlight the transformative potential of ITLS that integrate IoT and digital twin technologies. Empirical data from eight major cities in Malaysia show statistically significant improvements in travel time efficiency, congestion reduction, fuel consumption, CO_2 emissions, system reliability, and frequency of signal adjustments.

5.1.1. Technical and Operational Implications

Real-time Adaptation and Frequent Signal Adjustments: The significant increase in daily signal adjustments highlights the need for traffic management systems that can instantly respond to fluctuating road

Table 6 I CO2 Emissions Before and After ITLS Implementation

City	Before implementation (tons/day)	After Implementation (tons/day)	Reduction rate (%)
Kuala Lumpur	20.4	17.1	16.2
Penang	13.2	11.1	15.9
Johor Bahru	14.4	12.0	16.7
Shah Alam	11.5	9.6	16.5
Putrajaya	8.4	7.1	15.5
Cyberjaya	16.0	10.4	35.0
Kota Kinabalu	9.1	7.7	15.4
Kuching	8.9	7.5	15.7
Average	12.7	10.3	18.4

Table 7 I System Reliability Before and After ITLS Implementation

City	Running time (%)	Monthly downtime (hours)
Kuala Lumpur	97.8	16.2
Penang	98.2	13.3
Johor Bahru	98.0	14.6
Shah Alam	98.4	11.7
Putrajaya	98.6	10.2
Cyberjaya	99.2	5.8
Kota Kinabalu	97.9	15.3
Kuching	98.3	12.4
Average	98.3	12.4

Table 8 | Daily Signal Adjustments Before and After ITLS Implementation

City	Pre-implementation	Post-implementation	Increase (%)
Kuala Lumpur	80	295	268.8
Penang	55	205	272.7
Johor Bahru	60	230	283.3
Shah Alam	45	175	288.9
Putrajaya	35	140	300.0
Cyberjaya	50	180	260.0
Kota Kinabalu	38	145	281.6
Kuching	36	140	288.9
Average	49.9	188.8	280.5

conditions. IoT-driven controllers and digital twin models play a crucial role in facilitating these dynamic adaptations (Hashem et al., 2024).

Digital twin integration: integrating IoT gateways for data collection and cloud-based digital twin platforms for traffic simulation significantly improves decision-making (Irfan et al., 2024). The predictive power of the digital twin environment enables city managers to anticipate and mitigate congestion before it intensifies.

Scalability and Resiliency: The layered architectural design (including field, communications, processing, and application layers) is scalable, enabling incremental system expansion. In addition, power backup (UPS) and redundant communication channels minimize downtime, which is critical in high-density urban environments.

Environmental Sustainability: Significant reductions in fuel consumption and CO_2 emissions are consistent with broader green development goals (Zakari et al., 2022). These findings suggest that ITLS, when integrated into a city's sustainability agenda, can make a tangible contribution toward mitigating environmental impacts.

5.1.2. Economic Considerations

Cost Benefit Advantage: While the initial capital investment (for IoT sensors, communications upgrades, and cloud services) can be large, the reduction in congestion-related costs (lost productivity, excessive fuel use, and vehicle maintenance) supports a favorable long-term return on investment (ROI).

Scalable Deployment: Incremental deployment (e.g., focusing on high-priority intersections first) can help municipalities manage financial expenditures while reaping immediate benefits. Successful pilot projects can attract additional funding or incentives for broader system rollouts.

5.1.3. Policy and Governance Factors

Standardization and Interoperability: Unified data exchange protocols and sensor specifications simplify integration and reduce the complexity of integrating various traffic control units and cameras (Naveed et al., 2022).

Public-private partnerships: Partnering with technology companies and system integrators can offset capital costs and accelerate knowledge transfer. Clear procurement guidelines and performance-based contracts help align incentives.

Capacity Building: Facilities managers and traffic engineers need ongoing training in IoT data management, predictive analytics, and digital twin operations. Investment in skill development is critical to sustain long-term system performance.

Data Governance and Compliance: Harmonizing ITLS data streams with local cybersecurity laws (e.g., China’s Data Security Law) and ensuring locally hosted servers for sensitive traffic footage can be crucial to maintaining public trust and avoiding legal complications.

5.2. Implementation Framework for Chinese Citiess

Based on the quantitative evidence and operational insights gained from the MSTLM project, we attempt to articulate a strategic roadmap that can be used to deploy ITLS in Chinese urban environments. The framework recognizes the diversity of infrastructures, the complexity of systems, and the high population densities in many of China's urban areas. By integrating technical, operational, and policy-oriented strategies, the proposed implementation framework aims to simplify the deployment of ITLS for sustainable and smart urban traffic management.

In China’s context, high population densities and complex governance structures necessitate greater emphasis on inter-agency coordination. Our pilot-based approach could be initially tested in Tier 1 cities (e.g., Shanghai or Guangzhou) before scaling to mid-sized cities.

5.2.1. Phased Deployment Strategy

A three-phase approach ensures that ITLS implementation is systematic, adaptive, and scalable. Each phase addresses key considerations in infrastructure, technology, stakeholder engagement, and policy alignment.

5.2.1.1. Phase 1: Infrastructure Assessment and Planning

1) Network Evaluation

- Bandwidth and Coverage: Conduct city-wide surveys to evaluate existing cellular networks (e.g., 4G/LTE, 5G) and fiber backbones. Identify zones with inadequate coverage and plan expansions or upgrades.
- Latency Requirements: Set benchmarks for maximum permissible latency (e.g., 100 ms) to support real-time signal adjustments and IoT data streaming.

2) Legacy System Compatibility

- Controller and Sensor Audit: Catalog existing traffic controllers, sensors, and traffic lights. Determine which can be integrated via compatibility modules (e.g., serial-to-Ethernet converters) and which require replacement.
- Protocol Alignment: Adopt standardized communication protocols (e.g., MQTT, CoAP, Ethernet) to minimize integration conflicts and ensure consistent data formatting.

3) Stakeholder Engagement

- Inter-departmental Collaboration: Form a steering committee with representatives from transportation, IT, public security, and urban planning agencies to unify decision-making.
- Public-Private Partnerships (PPPs): Explore collaborations with telecommunications companies and technology vendors, leveraging private-sector expertise and shared investment models.

5.2.1.2. Phase 2: Pilot Implementation

1) High-Priority Intersections

- Site Selection Criteria: Focus on intersections with chronic congestion, high accident rates, or strategic importance (e.g., CBDs, access points to highways).
- Pilot Scale: Start with a manageable number of intersections (e.g., 10–20) to validate the technical architecture and fine-tune system parameters before city-wide rollout.

2) Core ITLS Components

- IoT Gateways and Cloud Services: Install IoT gateways at selected intersections and configure cloud servers to process incoming data in real time.
- Digital Twin Panels: Develop interactive dashboards displaying real-time traffic flows, congestion indices, and predictive scenarios for each pilot site.
- Edge Processing: For latency-critical tasks, consider deploying edge computing nodes near intersections, reducing the round-trip time to cloud servers.

3) Performance Monitoring and Adjustment

- Pilot Selection: We recommend a 6-month pilot cycle to capture seasonal variations in traffic patterns.
- KPI Tracking: Continuously monitor travel times, congestion indices, and fuel consumption metrics via live dashboards.
- Iterative Fine-Tuning: Adjust signal timings and sensor calibration (e.g., camera angles, detection zones) based on real-time data and operator feedback.
- Public Feedback Loop: Integrate user feedback—particularly from drivers, commuters, and local businesses—to refine pilot implementation and bolster community support.

5.2.1.3. Phase 3: Full-Scale Rollout

1) City-Wide Integration

- Incremental Expansion: Deploy ITLS across all major intersections, prioritizing those with high traffic volume and strategic significance.
- Cluster-Based Rollout: Roll out in clusters (e.g., districts or zones) to manage complexity and consolidate data analytics for each area.

2) Adaptive Optimization

- Seasonal and Event-Based Adjustments: Use time series analysis to preemptively modify signal timings during holidays, special events, or seasonal peaks (e.g., monsoon seasons).
- Machine Learning Algorithms: Incorporate AI-driven pattern recognition to optimize signal timing, particularly for unpredictable traffic surges (e.g., accidents, sporting events).

3) Multi-Modal Integration

- Public Transit Synchronization: Align ITLS adjustments with bus rapid transit (BRT) or metro schedules, prioritizing public transport corridors during peak hours.
- Non-Motorized Modes: Implement pedestrian-friendly signal phases and consider bicycle lane integration, reducing vehicular dependency and supporting green mobility.

5.2.2. Technical Infrastructure Requirements

Reliable communication networks, scalable computing solutions, and robust security measures form the backbone of a well-functioning ITLS. Meeting these requirements ensures that frequent signal adjustments, real-time analytics, and digital twin simulations can be performed without technical bottlenecks.

5G/LTE Capacity Planning: Forecast data usage based on sensor density and update rates. Each intersection may generate multiple streams of video/telemetry data.

Secure Access Control: Implement multi-factor authentication (MFA) for control systems, ensuring only authorized personnel can modify signal parameters.

Facilities Maintenance Protocols: Establish regular cleaning, alignment checks, and firmware updates to minimize sensor drift or degradation.

IoT Protocol Compatibility: Promote uniform adoption of open standards (MQTT, CoAP) or widely used industrial protocols (e.g., Modbus over TCP) for ease of integration.

5.2.3. Risk Management

Comprehensive risk management addresses technical, operational, and stakeholder-related uncertainties. Proactive mitigation enhances system reliability, sustainability, and public acceptance.

Bridging Modules: Bridge Module: Prepare adapters/converters to connect older traffic controllers or sensors to modern IoT gateways. Greater compatibility with deployed devices, reduced costs and improved overall stability.

Scheduled Downtime: Enables facilities management teams to plan system updates and maintenance periods during off-peak hours to minimize disruptions.

Skill Shortages: Organize workshops and certification programs for facilities management teams focusing on system configuration, predictive analytics, and digital twin usage. Also develop a centralized repository of standard operating procedures (SOPs), lessons learned, and best practices that can be accessed by all departments.

5.3. Conclusion

The above framework provides a structured blueprint for Chinese cities seeking to deploy ITLS at scale. By dividing deployment into carefully managed phases, supported by a strong technical infrastructure and stakeholder collaboration, relevant government authorities can mitigate risk and ensure continuous performance improvement (Nübel et al., 2021). In addition, aligning the ITLS with broader city development strategies, particularly around environmental sustainability and economic viability, can enhance its effective long-term sustainability.

6. Conclusions and Recommendations

6.1. Summary of Research

Drawing empirical evidence from the MSTLM project, this thesis provides a rigorous exploration of an IoT-driven, digital twin-enhanced ITLS. By juxtaposing the theoretical foundations of adaptive traffic control with real-world data collected from eight major cities in Malaysia, this work confirms the transformative power of ITLS. From the outset, this research was driven by one overarching question: Can an IoT-centric layered architecture solution effectively reduce urban congestion and produce sustainable mobility outcomes?

The investigation addresses this issue by profiling multifaceted performance metrics, including travel time, congestion index, fuel consumption, CO_2 emissions, and overall system resilience. Chapters 1 through 5 provide the conceptual background, methodological framework, and detailed empirical findings, culminating in strategic recommendations for large-scale adoption in Chinese cities. This chapter summarizes the study, synthesizes the accumulated insights, describes the broader implications, and provides a roadmap for continued engagement in the scholarship and practice of ITLS.

6.2. Key Results

6.2.1. Efficacy Across Core Metrics

Empirical data demonstrates the significant enhancement of traffic flow and environmental indices. Travel time efficiency soared by an average of 37.7%, while the congestion index dropped by 38.5%, highlighting the real-time adaptability of ITLS. Meanwhile, daily fuel consumption dropped by 27.3% and CO_2 emissions by 18.4%. Taken together, these results underscore the system's ability to contribute to tangible sustainability gains in urban mobility.

6.2.2. Robust Technical Underpinnings

Empirical evidence demonstrates that a layered ITLS architecture, including field, communication, processing, and application layers, helps ensure system robustness. Supported by 5G/LTE networks, real-time data streaming facilitates instantaneous signal tuning, while digital twin environments optimize prediction (Maiwada et al., 2024). This synergy of edge processing and cloud analytics provides the foundation for near-seamless traffic orchestration, resulting in 98.3% operational uptime and minimal downtime.

6.2.3. Economic and Environmental Justifications

While the initial capitalization of IoT integrations and infrastructure upgrades may seem daunting, MSTLM data confirms the long-term return on investment (ROI). Reduced vehicle idle time, reduced accident risk, and streamlined traffic flow combine to lower operating costs and greenhouse gas emissions. As a result, cities ready to implement ITLS will realize economic relief and ecological dividends over time, creating a virtuous cycle.

6.2.4. Policy-Driven Scalability

Aligning system deployments with an incremental strategy framework (especially in the areas of standardization, interoperability, and public-private collaboration) becomes critical. Harmonized protocols and centralized data governance accelerate citywide deployments, ensuring that Advanced Traffic Management is no longer an isolated pilot, but evolves into a sustainable and scalable growing smart city effort.

6.3. Contributions to Knowledge

6.3.1. Empirical Validation in Emerging Urban Contexts

While adaptive signal control is not novel, this dissertation enriches the literature by applying IoT and digital twin insights to a rapidly urbanizing region. The empirical rigor across multiple cities goes beyond the single case studies usually limited to advanced metropolitan areas, thus broadening the generalizability of ITLS efficacy.

6.3.2. Fusion of Technological and Environmental Outcomes

By focusing on simultaneous improvements in system reliability and environmental metrics, the study highlights an often-overlooked synergy: high-frequency signal tuning can both smooth traffic and achieve carbon containment. This dual emphasis amplifies the argument for integrated urban planning that encompasses IoT-based solutions within broader sustainability policies.

6.3.3. Blueprint for Collaborative Governance

Beyond the purely technical findings, the study reveals that governance - particularly cross-sectoral committees, data sovereignty issues, and PPP mechanisms - provides a more nuanced view of how ITLS can thrive in complex urban ecosystems. The interplay of shared responsibility, standardized protocols, and capacity building underscores the socio-technical nature of truly smart traffic management.

6.4. Future Research Directions

6.4.1. Synergistic Integration With Autonomous Vehicles

As autonomous driving technologies mature, it is critical to study the interactions between ITLS and connected fleets. Machine-to-machine negotiation at intersections, dynamic re-routing, and advanced collision avoidance protocols require cohesive research that connects traffic engineering and AI (Bittencourt et al., 2024).

6.4.2. Advanced Machine Learning Algorithms

Future implementations may deploy reinforcement learning or deep neural networks to continuously optimize intersection control with minimal human intervention (Elallid et al., 2022). Such algorithms could leverage real-time "experience" to outperform static traffic signal planning, especially in the presence of unpredictable traffic surges.

6.4.3. Potential of Different Types of Cities

We encourage multi-city replication studies in geographically diverse Chinese provinces to validate the universal applicability of these findings and to capture potential regional constraints such as rural vs. urban traffic patterns and industrial vs. service-oriented city layouts.

6.5. Concluding Remarks

In an era of burgeoning urban populations and demands outpacing outdated traffic management methods, smart traffic light systems powered by IoT data streams and digital twin predictions represent beacons of practical innovation and open up possibilities for further visions of facilities management.

While MSTLM experience exemplifies these benefits, the proposed implementation framework and policy recommendations aim to inspire similar successes in China's urban landscape. Each metropolis has its own nuanced challenges and prospects, and these guidelines can be adapted to local realities, opening the way for a more fluid, low-carbon, and citizen-centered transportation ecosystem. Ultimately, the synergy of forward-thinking governance, big data algorithms, and AI may well make the notion of "traffic chaos" a footnote in history, replaced by a dynamic, sustainable, and intelligent urban tapestry that harmoniously blends technology and humanity.

References

1. Adel, A., & HS Alani, N. (2024). Human-centric collaboration and industry 5.0 framework in smart cities and communities: Fostering sustainable development goals 3, 4, 9, and 11 in society 5.0. Smart Cities, 7(4), Article 4. https://doi.org/10.3390/smartcities7040068
2. Albouq, S. S., Sen, A. A. A., Almashf, N., Yamin, M., Alshanqiti, A., & Bahbouh, N. M. (2022). A survey of interoperability challenges and solutions for dealing with them in IoT environment. IEEE Access, 10, 36416–36428. IEEE Access. https://doi.org/10.1109/ACCESS.2022.3162219
3. Alfandi, O., Khanji, S., Ahmad, L., & Khattak, A. (2021). A survey on boosting IoT security and privacy through blockchain. Cluster Computing, 24(1), 37–55. https://doi.org/10.1007/s10586-020-03137-8
4. Almutairi, R., Bergami, G., & Morgan, G. (2024). Advancements and challenges in IoT simulators: A comprehensive review. Sensors, 24(5), Article 5. https://doi.org/10.3390/s24051511
5. Bibri S. E. (2021). Data-driven smart sustainable cities of the future: An evidence synthesis approach to a comprehensive state-of-the-art literature review. Sustainable Futures, 3, 100047. https://doi.org/10.1016/j.sftr.2021.100047
6. Bibri, S. E., & Krogstie, J. (2020). Environmentally data-driven smart sustainable cities: Applied innovative solutions for energy efficiency, pollution reduction, and urban metabolism. Energy Informatics, 3(1), 29. https://doi.org/10.1186/s42162-020-00130-8
7. Bittencourt, J. C. N., Costa, D. G., Portugal, P., & Vasques, F. (2024). A survey on adaptive smart urban systems. IEEE Access, 12, 102826–102850. IEEE Access. https://doi.org/10.1109/ACCESS.2024.3433381
8. Botín-Sanabria, D. M., Mihaita, A.-S., Peimbert-García, R. E., Ramírez-Moreno, M. A., Ramírez-Mendoza, R. A., & Lozoya-Santos, J. de J. (2022). Digital twin technology challenges and applications: A comprehensive review. Remote Sensing, 14(6), Article 6. https://doi.org/10.3390/rs14061335
9. Elallid, B. B., Benamar, N., Hafid, A. S., Rachidi, T., & Mrani, N. (2022). A comprehensive survey on the application of deep and reinforcement learning approaches in autonomous driving. Journal of King Saud University, Computer and Information Sciences, 34(9), 7366–7390. https://doi.org/10.1016/j.jksuci.2022.03.013
10. Elassy, M., Al-Hattab, M., Takruri, M., & Badawi, S. (2024). Intelligent transportation systems for sustainable smart cities. Transportation Engineering, 16, 100252. https://doi.org/10.1016/j.treng.2024.100252
11. Ersan, M., Irmak, E., & Colak, A. M. (2024). Applications, insights and implications of digital twins in smart city management. 2024 12th International Conference on Smart Grid (icSmartGrid), 378–383. https://doi.org/10.1109/icSmartGrid61824.2024.10578291
12. Glazener A., Sanchez K., Ramani T., Zietsman J., Nieuwenhuijsen M. J., Mindell J. S., Fox M., & Khreis H. (2021). Fourteen pathways between urban transportation and health: A conceptual model and literature review. Journal of Transport & Health, 21, 101070. https://doi.org/10.1016/j.jth.2021.101070
13. Gunes, F., Bayrakli, S., & Zaim, A. H. (2021). Smart cities and data analytics for intelligent transportation systems: An analytical model for scheduling phases and traffic lights at signalized intersections. Applied Sci-

ences, 11(15), Article 15. https://doi.org/10.3390/app11156816
14. Hashem, I. A., Siddiqa, A., Alaba, F. A., Bilal, M., & Alhashmi, S. M. (2024). Distributed intelligence for IoT-based smart cities: A survey. Neural Computing and Applications, 36(27), 16621–16656. https://doi.org/10.1007/s00521-024-10136-y
15. Hui, C. X., Dan, G., Alamri, S., & Toghraie, D. (2023). Greening smart cities: An investigation of the integration of urban natural resources and smart city technologies for promoting environmental sustainability. Sustainable Cities and Society, 99, 104985. https://doi.org/10.1016/j.scs.2023.104985
16. Irfan, M. S., Dasgupta, S., & Rahman, M. (2024). Toward transportation digital twin systems for traffic safety and mobility: A review. IEEE Internet of Things Journal, 11(14), 24581–24603. IEEE Internet of Things Journal. https://doi.org/10.1109/JIOT.2024.3395186
17. Javaid M., Haleem A., & Suman R. (2023). Digital Twin applications toward Industry 4.0: A Review. Cognitive Robotics, 3, 71–92. https://doi.org/10.1016/j.cogr.2023.04.003
18. Kajiita, R. M., & Kang'ethe, S. M. (2024). Socio-economic dynamics inhibiting inclusive urban economic development: Implications for sustainable urban development in south african cities. Sustainability, 16(7), Article 7. https://doi.org/10.3390/su16072803
19. Khan, S. I., Kaur, C., Al Ansari, M. S., Muda, I., Borda, R. F. C., & Bala, B. K. (2023). Implementation of cloud based IoT technology in manufacturing industry for smart control of manufacturing process. International Journal on Interactive Design and Manufacturing (IJIDeM). https://doi.org/10.1007/s12008-023-01366-w
20. Kuang Y., Yen B. T. H., Suprun E., & Sahin O. (2019). A soft traffic management approach for achieving environmentally sustainable and economically viable outcomes: An Australian case study. Journal of Environmental Management, 237, 379–386. https://doi.org/10.1016/j.jenvman.2019.02.087
21. Kušić K., Schumann R., & Ivanjko E. (2023). A digital twin in transportation: Real-time synergy of traffic data streams and simulation for virtualizing motorway dynamics. Advanced Engineering Informatics, 55, 101858. https://doi.org/10.1016/j.aei.2022.101858
22. Leroutier M., & Quirion P. (2023). Tackling Car Emissions in Urban Areas: Shift, Avoid, Improve. Ecological Economics, 213, 107951. https://doi.org/10.1016/j.ecolecon.2023.107951
23. Li, C. Z., Guo, Z., Su, D., Xiao, B., & Tam, V. W. Y. (2022). The application of advanced information technologies in civil infrastructure construction and maintenance. Sustainability, 14(13), Article 13. https://doi.org/10.3390/su14137761
24. Liu, H., Chen, W., Sun, S., Yu, J., Zhang, Y., & Ye, C. (2024). Revisiting china's urban transition from the perspective of urbanisation: A critical review and analysis. Sustainability, 16(10), Article 10. https://doi.org/10.3390/su16104122
25. Magazzino C., & Mele M. (2021). On the relationship between transportation infrastructure and economic development in China. Research in Transportation Economics, 88, 100947. https://doi.org/10.1016/j.retrec.2020.100947
26. Maiwada, U. D., Danyaro, K. U., Sarlan, A., Liew, M. S., Taiwo, A., & Audi, U. I. (2024). Energy efficiency in 5G systems: A systematic literature review. International Journal of Knowledge-Based and Intelligent Engineering Systems, 28(1), 93–132. https://doi.org/10.3233/KES-230061
27. Molina, J. A., Giménez-Nadal, J. I., & Velilla, J. (2020). Sustainable commuting: Results from a social approach and international evidence on carpooling. Sustainability, 12(22), Article 22. https://doi.org/10.3390/su12229587
28. Molina, L. T., Velasco, E., Retama, A., & Zavala, M. (2019). Experience from integrated air quality management in the Mexico city metropolitan area and Singapore. Atmosphere, 10(9), Article 9. https://doi.org/10.3390/atmos10090512
29. Musa, A. A., Malami, S. I., Alanazi, F., Ounaies, W., Alshammari, M., & Haruna, S. I. (2023). Sustainable traffic management for smart cities using internet-of-things-oriented intelligent transportation systems (ITS): Challenges and recommendations. Sustainability, 15(13), Article 13. https://doi.org/10.3390/su15139859
30. Naveed, Q. N., Alqahtani, H., Khan, R. U., Almakdi, S., Alshehri, M., & Abdul Rasheed, M. A. (2022). An intelligent traffic surveillance system using integrated wireless sensor network and improved phase timing optimization. Sensors, 22(9), Article 9. https://doi.org/10.3390/s22093333
31. Nübel, K., Bühler, M. M., & Jelinek, T. (2021). Federated digital platforms: Value chain integration for sustainable infrastructure planning and delivery. Sustainability, 13(16), Article 16. https://doi.org/10.3390/su13168996
32. Qian, C., Liu, X., Ripley, C., Qian, M., Liang, F., & Yu, W. (2022). Digital twin—cyber replica of physical things: Architecture, applications and future research directions. Future Internet, 14(2), Article 2. https://doi.org/10.3390/fi14020064
33. Rai, S. C., Nayak, S. P., Acharya, B., Gerogiannis, V. C., Kanavos, A., & Panagiotakopoulos, T. (2023). ITSS: An intelligent traffic signaling system based on an IoT infrastructure. Electronics, 12(5), Article 5. https://doi.org/10.3390/electronics12051177
34. Savall-Mañó M., Ribas I., & Estrada M. (2024). A strategic variable fee for business-to-consumer carriers: A case study in Barcelona. Transportation Research Part A: Policy and Practice, 190, 104233. https://doi.org/10.1016/j.tra.2024.104233
35. Sefati, S. S., & Halunga, S. (2023). Ultra-reliability and low-latency communications on the internet of things based on 5G network: Literature review, classification, and future research view. Transactions on Emerging Telecommunications Technologies, 34(6), e4770. https://doi.org/10.1002/ett.4770
36. Seoane, V., Garcia-Rubio, C., Almenares, F., & Campo, C. (2021). Performance evaluation of CoAP and MQTT with security support for IoT environments. Computer Networks, 197, 108338. https://doi.org/10.1016/j.comnet.2021.108338

37. Toulni, H., Miyara, M., Filali, Y., & Tékouabou, S. C. K. (2023). Preventing urban traffic congestion using VANET technology in urban area. E3S Web of Conferences, 418, 2005. https://doi.org/10.1051/e3sconf/202341802005
38. Werbińska-Wojciechowska, S., Giel, R., & Winiarska, K. (2024). Digital twin approach for operation and maintenance of transportation system—Systematic review. Sensors, 24(18), Article 18. https://doi.org/10.3390/s24186069
39. Wu, Q. (2023). New trends and technologies in facilities management in China: The dual impact of environmental protection and digitalisation. 1212–1218. https://doi.org/10.2991/978-94-6463-256-9_123
40. Wu, Q. (2024). Application of circular economy in facility maintenance and management: Moving towards a low carbon future. In K. Papadikis, C. Zhang, S. Tang, E. Liu, & L. Di Sarno (Eds.), Towards a Carbon Neutral Future (Vol. 393, pp. 249–257). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-7965-3_23
41. Zakari, A., Khan, I., Tan, D., Alvarado, R., & Dagar, V. (2022). Energy efficiency and sustainable development goals (SDGs). Energy, 239, 122365. https://doi.org/10.1016/j.energy.2021.122365