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A Survey on AI-Based Adaptive Traffic Signal Control Systems for Smart Cities

Dr. Prashant Wakhare, Ms. Mahewish Saudagar, Ms. Kausar Shaikh, Ms. Pooja Satbhai
AISSMS Institute of Information Technology, Pune, Maharashtra, India
prashant.wakhare@aissmsioit.org, mahewish.saudagar@aissmsioit.org
kausar.shaikh@aissmsioit.org, pooja.satbhai@aissmsioit.org

Abstract: *Traffic congestion has become a major issue in urban areas due to the rapid growth in the number of vehicles and the limitations of traditional fixed-time traffic signal systems. These systems operate on predefined timings and cannot adapt to real-time traffic conditions, which often results in longer waiting times, increased fuel consumption, and higher levels of environmental pollution [20]. To address these challenges, recent research has focused on the development of intelligent and adaptive traffic signal control systems using technologies such as Artificial Intelligence, Machine Learning, Deep Learning, and Reinforcement Learning [9]. Computer vision techniques, particularly models like YOLO, are widely used for detecting vehicles in real time and estimating traffic density [4]. At the same time, technologies like IoT and edge computing support efficient data collection and enable faster processing of traffic information [1], [16].*

This survey paper examines recent studies (2025–2026) related to smart traffic management systems. It also includes approaches developed for emergency vehicle prioritization and traffic prediction using predictive analytics [3], [11]. Various methods are compared based on factors such as efficiency, scalability, and real-time performance. The review indicates that AI-based adaptive traffic systems can significantly improve traffic flow and help reduce congestion. However, implementing these systems on a large scale remains challenging due to high costs and system complexity [5], [14]. Future research should focus on developing solutions that are more cost-effective, scalable, and practical for real-world smart city applications.

Keywords: Traffic Congestion, Artificial Intelligence (AI), Machine Learning (ML), Deep Learning, Reinforcement Learning, Computer Vision, YOLO, Adaptive Traffic Signal Control, Smart Traffic Management.

I. INTRODUCTION

Rapid urbanization along with the continuous rise in the number of vehicles has made traffic congestion a serious issue in modern cities. Managing traffic efficiently has become important to reduce delays, fuel usage, and environmental pollution. Most traditional traffic signal systems work on fixed-time control, where signal timings are already set and do not change based on actual traffic conditions. Because of this, traffic flow often becomes inefficient, especially during peak hours or unexpected situations [1].

To deal with these limitations, there is an increasing demand for intelligent and adaptive traffic signal control systems. Recent developments in technologies such as Artificial Intelligence, Machine Learning, and computer vision have made it possible to design smarter traffic management solutions. These systems can analyze real-time traffic data, detect vehicle density, and adjust signal timings dynamically to improve traffic flow [4][10].

Along with this, technologies like the Internet of Things (IoT) and edge computing play an important role in collecting and processing traffic data in real time. Computer vision methods, especially object detection models such as YOLO, are widely used for accurate vehicle detection and estimating traffic density. In addition to basic traffic control, modern systems also include features like emergency vehicle prioritization and traffic prediction, which help improve overall efficiency [15].

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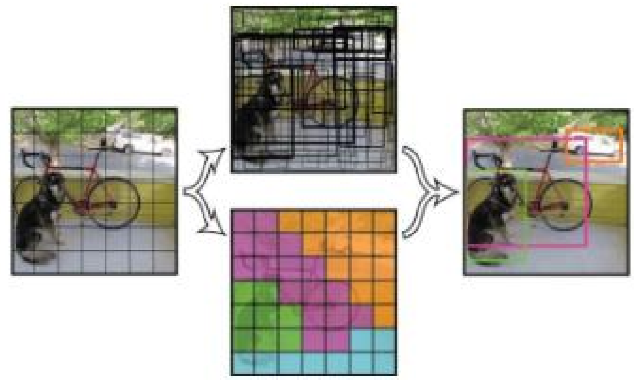

Figure2: YOLO architecture [8]

Figure 1: Illustration of the detection of vehicles per line [11]

II. LITERATURE SURVEY

In paper **[1]**, the authors proposed a smart traffic management system that combines IoT and Artificial Intelligence. The system gathers real-time traffic data using sensors and improves signal control. However, applying this system on a large scale is difficult because it requires a wide network of sensors and supporting infrastructure, which increases the overall cost. In paper **[2]**, a machine learning-based method is introduced to optimize traffic signals by considering environmental factors such as weather and traffic patterns. Although it improves decision-making, it depends on large datasets and high computational resources, which makes real-world implementation challenging. In paper **[3]**, an intelligent system for emergency vehicle control is developed using machine learning to provide signal priority. While the system performs well, it relies on accurate detection and communication systems, which may not always be reliable in every location. In paper **[4]**, a deep learning-based approach using the YOLO model is presented for real-time vehicle detection and adaptive signal control. The model gives accurate results, but it requires high-performance hardware and continuous video processing, increasing cost and limiting its use on a large scale. In paper **[5]**, an adaptive traffic signal system based on reinforcement learning and thermal sensors is proposed. It helps improve traffic flow, but the use of specialized sensors makes installation expensive.

In paper **[6]**, the authors reviewed evolutionary and swarm intelligence techniques for optimizing traffic signals. These methods provide efficient solutions, but their computational complexity makes real-time implementation difficult. In paper **[7]**, computer vision techniques are used to estimate traffic density from images and videos. Although the system improves traffic analysis, its performance can be affected by environmental conditions such as lighting and weather. In paper **[8]**, a real-time traffic signal optimization system based on vehicle detection is discussed. It improves traffic flow but requires continuous monitoring and processing, which demands strong hardware support. In paper **[9]**, the role of

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Artificial Intelligence and Machine Learning in smart transportation systems is analyzed. These technologies enhance efficiency, but their implementation requires significant investment and infrastructure, limiting widespread adoption. In paper **[10]**, an adaptive traffic signal control system based on object detection is presented. The system adjusts signal timing dynamically according to traffic density and improves overall management.

In paper **[11]**, predictive analytics is used to estimate future traffic volume for better planning and control. The effectiveness of this system depends on the availability of accurate historical data. In paper **[12]**, a deep reinforcement learning-based traffic signal control system is proposed, where the model learns optimal signal timing by interacting with traffic conditions. However, training such models requires time and high computational power. In paper **[13]**, deep learning techniques are applied for real-time vehicle classification, which supports traffic monitoring and analysis. In paper **[14]**, an IoT-based traffic prediction and signal control system is designed for smart cities. While useful, it increases system complexity and maintenance cost due to dependency on IoT devices and network infrastructure. In paper **[15]**, an intelligent traffic control system combining YOLO and reinforcement learning is proposed. This integration improves performance but also adds to system complexity and implementation challenges.

In paper **[16]**, an edge-based real-time adaptive traffic signal system using YOLO is introduced. It reduces delay and enables faster decision-making, but requires deployment of edge devices at each junction, increasing cost. In paper **[17]**, the combination of IoT and AI for smart traffic monitoring is discussed, showing improvements in urban mobility and traffic efficiency. In paper **[18]**, a survey on AI-driven adaptive traffic signal systems using Edge-IoT architecture is presented, highlighting both benefits and real-world challenges. In paper **[19]**, a sensor-based adaptive traffic signal control system is proposed. While multiple sensors improve accuracy, they also increase infrastructure cost, making large-scale deployment difficult. In paper **[20]**, a review of self-adaptive traffic signal systems is provided, discussing different techniques, challenges, and possible future research directions.

Sr. No.	Author & Year (Citation)	Title	Journal	Advantages	Disadvantages
1	Abd et al. (2025) [1]	Smart Traffic System using IoT & AI	IJSAT	Supports real-time monitoring and improves traffic signal control	Requires high infrastructure investment
2	Akpan et al. (2026) [2]	Traffic Optimization using ML & Environmental Data	AI & Applications	Enhances decision-making using multiple factors	Needs large datasets and is computationally complex
3	Anonymous (2025) [3]	Emergency Vehicle Control System	—	Enables faster response for emergency vehicles	Depends on reliable detection systems
4	Ayodeji et al. (2025) [4]	YOLO-based Traffic Control Model	IJCA	Provides accurate vehicle detection	Requires high processing power
5	Balashov et al. (2025) [5]	RL with Thermal Sensors	Results in Engineering	Helps in reducing traffic congestion	Uses expensive sensors
6	Bhattacharyya et al. (2026) [6]	Swarm & Evolutionary Optimization	AI Review	Offers efficient optimization techniques	Difficult to implement in real-time due to complexity

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7	Freese & Hoffman (2025) [7]	Traffic Density using Computer Vision	SATC	Accurately estimates traffic density	Performance affected by weather conditions
8	Fathimunnisa et al. (2025) [8]	Real-time Traffic Optimization	—	Improves overall traffic flow	Needs continuous monitoring and processing
9	Haq et al. (2026) [9]	AI in Smart Transportation	GRJNST	Improves safety and traffic flow	High implementation cost
10	Khan et al. (2025) [10]	Object Detection-based Signal Control	IEEE	Enables dynamic signal timing	Depends on detection accuracy
11	Kaur et al. (2025) [11]	Predictive Traffic Analytics	IEEE	Helps in forecasting future traffic conditions	Accuracy depends on data quality
12	Li et al. (2026) [12]	DRL-based Traffic Control	IEEE TVT	Works effectively in practical scenarios	Requires high computational resources
13	Maurya et al. (2025) [13]	Vehicle Classification using DL	Engineering Reports	Improves traffic data analysis	Cannot function as a standalone system
14	Neelakandan et al. (2021) [14]	IoT Traffic Prediction System	Soft Computing	Suitable for smart city applications	High maintenance cost
15	Parimala et al. (2025) [15]	YOLO + RL Traffic System	ICCSCE	Supports real-time adaptation	Complex system integration
16	Raza et al. (2025) [16]	Edge-based Traffic Control	IEEE Access	Enables faster processing and response	Expensive to deploy
17	Saini & Sharma (2025) [17]	IoT + AI Monitoring	ACM	Improves traffic mobility	Faces scalability challenges
18	Vishwakarma (2026) [18]	Edge-IoT Traffic Survey	IJAI	Provides a detailed overview	Issues in real-world deployment
19	Wang & Shao (2025) [19]	Sensor-based Traffic Control	Sensors	Supports dynamic traffic optimization	High cost of sensors
20	Wang et al. (2018) [20]	Adaptive Traffic Review	JAT	Gives useful future insights	Challenges in implementation

The review of the selected research papers shows that most existing traffic management systems make use of advanced technologies such as Artificial Intelligence, Machine Learning, Deep Learning, and Reinforcement Learning to support dynamic decision-making. Computer vision techniques, especially models like YOLO, are commonly used for real-time vehicle detection and traffic density estimation, while technologies like the Internet of Things (IoT) and edge computing help in efficient data collection and faster processing with low delay. Many studies also include features such as emergency vehicle prioritization and the use of predictive analytics for traffic forecasting. However, despite these advancements, several challenges still remain, including high implementation cost, complex infrastructure

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requirements, and difficulties in large-scale deployment. Based on these observations, there is a need to develop traffic management systems that are cost-effective, scalable, and efficient, combining real-time vehicle detection with adaptive signal control while keeping computational and infrastructure requirements manageable for practical use in smart city environments.

III. FUTURE SCOPE

Future research in intelligent traffic management systems should focus on developing solutions that are both cost-effective and scalable, especially to address the issues of high implementation cost and system complexity. The use of advanced technologies such as 5G communication, improved edge computing, and more efficient machine learning models can help in faster data processing and better decision-making in real time. In addition, improving coordination between multiple traffic intersections and enhancing vehicle detection and traffic prediction under different environmental conditions can further improve traffic flow. The development of fully automated traffic signal systems, along with vehicle-to-infrastructure communication, can play an important role in building more efficient and reliable transportation systems for future smart cities.

IV. CONCLUSION

This survey paper studies recent research on intelligent and adaptive traffic signal control systems that aim to overcome the limitations of traditional fixed-time traffic signals. It highlights the use of technologies such as Artificial Intelligence, Machine Learning, Deep Learning, Reinforcement Learning, and computer vision for real-time vehicle detection and dynamic signal control. From the analysis, it is clear that these systems help in improving traffic flow, reducing congestion, and increasing overall transportation efficiency. However, there are still challenges such as high implementation cost, system complexity, and the need for proper infrastructure, which limit their large-scale adoption. Even with these issues, intelligent traffic management systems show strong potential for modern urban transportation, and with further improvements in scalability and cost-effectiveness, they can play an important role in the development of smart and sustainable cities.

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