



AI-Driven Digital Twin System with Quantum Optimization for Smart Traffic Analysis and Control

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ABSTRACT - The fast pace of urban development and the ever-growing number of vehicles that move in urban areas have caused increased levels of congestion at urban intersections, leading to the need for intelligent adaptive and predictive solutions for traffic management. This work presents an AI-Driven Digital Twin System with Quantum Optimization for Smart Traffic Analysis and Control. The system will perform traffic monitoring and adaptive signal control at four-way intersections in real-time. To achieve this aim, the system will create a digital twin of the physical traffic environment which would enable visualizing and analyzing traffic flows, vehicle movements, signals' statuses, and optimized traffic conditions. A computer vision pipeline, which includes OpenCV, YOLOv8, and Byte Track algorithms for vehicle detection, classification, and multi-object tracking along north, south, east, and west directions, will be a part of the system. To improve detection accuracy and robustness, input video streams will be preprocessed with Median Blur and Contrast Limited Adaptive Histogram Equalization (CLAHE). Also, Non-Maximum Suppression (NMS) and majority voting will be applied to improve classification results. Rolling density estimation will help in continuous assessment of traffic conditions based on detected and tracked vehicles. For the adaptive signal control, Webster's formula will be utilized to determine the initial values of the signal cycle and other parameters of the timing. To optimize traffic conditions, a Quadratic Unconstrained Binary Optimization (QUBO) model will be defined and solved by the Quantum Approximate Optimization Algorithm (QAOA) using the Cirq library of quantum computing. In addition, the system will include a Long Short-Term Memory (LSTM) model, implemented with PyTorch, to predict future traffic conditions. Emergency vehicle detection and alert messaging will be used to support traffic prioritization. A 2D digital twin simulation with Pillow will represent visually the four-way intersection, vehicle movements, traffic density, signals' statuses, and optimized signal timings. The whole system will be embedded into the web portal, built using Django framework and SQLite as the backend database to authenticate users, manage videos, analyze traffic conditions, optimize signals, make predictions, and save system records. Thus, the integration of computer vision, deep learning, predictive analytics, quantum optimization, and digital twin into one web-based system will make a contribution to smart city transportation management and adaptive traffic control.

Keywords: Digital Twin, Intelligent Transportation Systems (ITS), Smart Traffic Management, Adaptive Signal Control, YOLOv8, OpenCV, Byte Track, Vehicle Classification, Traffic Density Estimation, QUBO, QAOA, Cirq, Webster's Formula, LSTM, PyTorch, Emergency Vehicle Detection, Django, SQLite

I. INTRODUCTION

There is a trend of urbanization, increase in the number of vehicles on the road, and development of the network infrastructure of transport system in the modern cities, which has caused traffic jam. The traffic signals in use are preprogrammed with fixed timings and such kind of fixed timing signals do not work under varying traffic conditions. There may be low efficiency of capacity utilization, time wasting, additional fuel burning, and pollution by the dangerous gases due to such static control. Another problem is associated with four-way intersections when the traffic flows in different directions have varying traffic loads. It is possible that the ambulances and the fire-engines are unable to find their way out through traffic jams.

But thanks to the emergence of the Digital Twin Technology, creation of such a system becomes possible. Digital twin is a model of the real physical environment that can constantly be adjusted depending on the data obtained from the physical world. In this research, a digital twin of a four-way traffic intersection will be created. Digital twin will be a 2D dynamic model that takes into account some characteristics such as vehicle movements, traffic density, traffic lights and optimal signal timings. By using the combination of traffic data extracted from videos and a digital twin of the intersection, we will be able to create a system capable of monitoring, simulating and predicting the traffic state. The system will be consisted of AI-Driven Digital Twin System with Quantum Optimization for Smart Traffic Analysis and Control. The traffic analysis part will include the processing of the video streams corresponding to the North, South, East and West directions of a four-way intersection. OpenCV library will be used for video stream processing and enhancing, while YOLOv8 will be used for object detection and classification. Byte Track library will be used for object tracking that maintains identities of the tracked objects in consecutive video frames. TO: The non-maximum suppression algorithm will assist in eliminating overlapping boxes and the majority vote technique will enhance the consistency of classification. Alongside the traffic flow measurement in real-time, the methodology also uses the approach of predictions and optimization to deal with the adaptive traffic signal control problem. The traffic flow is considered an input for LSTM prediction model in Py Torch, which will predict the future traffic state. Predictions will bring additional information regarding possible traffic congestions and assist in proactive traffic signal management. Webster's formula is used to calculate basic parameters of traffic signals and cycle length. Signal-control problem is modeled as QUBO problem with objective functions and constraints defined through mathematical models. The Quantum Approximate Optimization Algorithm (QAOA) provided in Cirq library is used to optimize signals phases.. Combining classical traffic engineering algorithms with quantum optimization provides a method for exploring adaptive traffic signal control based on current and predicted traffic state.

Another element of the system addresses detection and creation of alerts about the presence of emergency vehicles. When an emergency vehicle is detected on the traffic video, an alert is created, and the information can be used in the adaptive traffic management. Thus, emergency traffic situations will be taken into account within the digital twin. The 2D digital twin simulation is developed by means of the Pillow Python library. It presents a visualization of the four-way intersection, vehicle positions, traffic density, traffic signal states, and optimized signal states.

In order to offer an integrated and convenient interface, all the components of the system are implemented within a Django-based web portal. The web portal offers user authentication, video uploading from four directions, traffic-analysis results, results from the processing of output videos, traffic density, quantum-optimization results, LSTM-based predictions for the future, emergency vehicles notification, and visualization of 2D digital twin. In order to store the information about users, uploaded videos, traffic-analysis results, prediction results, signal-optimization results, and other data related to the system, an SQLite database is employed.

Thus, this framework is intended to show how the technologies of computer vision, deep learning, traffic prediction, quantum optimization, digital twin simulation, and web technologies can be integrated into a unified architecture. Through constant traffic analysis, forecasting of future demands, making optimal decisions on traffic-signal control, detection of emergency vehicles, and modeling of the intersection using the 2D digital twin, a framework for building intelligent transportation solutions for smart cities can be laid out.

II. LITERATURE SURVEY

As per the recent literature regarding urban traffic management, one of the crucial paradigm changes includes moving from static timers to a dynamic traffic management system using IoT and AI (Zia et al., 2018; Phand et

al., 2024). Although the early methods included successful use of sensors network for recalibration of signals, the problem of insufficient spatial coverage was encountered in many cases (Kumar & Kaur, 2021). Therefore, current solutions have increasingly been moving to use computer vision architectures such as YOLO for estimation of traffic density using videos collected by cameras. However, such methodologies are reactive towards current traffic congestion and do not provide any prediction feature. Our proposed digital twin includes reliable vehicle tracking (Byte Track) coupled with time-series model (LSTM). One of the closely related recent studies includes that of Sourav et al. (2026), where full-fledged AI-based traffic control system design was done by implementing YOLOv8 along with Python-Flask backend and React.js frontend. This solution offers traffic control through calculation of the density of vehicles in different lanes and assigns corresponding timings of signal, which is significantly more efficient than the traditional static timer approach. It resulted in the 30% decrease in average waiting time at junctions and 25% decrease in accidents caused by it. Furthermore, it was shown that the suggested solution can automatically prioritize emergency vehicles which demonstrates the possibility to use scalable open-source computer vision solutions for modern smart cities. Expanding on the concept of predictive traffic control, Sasikala et al. (2025) introduced an intelligent traffic signal control system that uses Convolutional Neural Networks (CNNs) and image processing. Significantly, the suggested model employs intelligent agents to evaluate speed and number of cars using cameras, which is a major factor in detecting congestion. Whereas the speed of road traffic was estimated instead of the number of vehicles, the artificial neural network proved its exceptional level of accuracy (the Mean Absolute Percentage Error MAPE was just 1.3%). This algorithm is based on the Python and OpenCV frameworks, illustrating how often the combination of speed estimation and neural networks predictions is used in modern urban mobility research. Representing the real-life application of deep learning for traffic light control at the intersections, Reddy and Sree (2024) designed an AI solution for traffic lights that can handle different types of vehicles. Their model uses the YOLOv3 algorithm for the detection and counting of bicycles, cars, buses, and trucks on video. Through image processing using the Python programming language, they have been able to determine the road density at any particular moment, which is then used by the microcontroller to control the time spent on each green light. This system helps deal with the inefficiency created by pre-programming traffic lights, as this causes the waiting of an empty lane. In highlighting the advantages of using intelligent transport to minimize the negative impact on the environment and promote sustainable development, Kadam et al. (2025) introduced an AI-based adaptive traffic control system that is driven by vehicle detection based on YOLO. This technology revolutionizes the existing model by shifting from the traditional static configuration of signals to a more dynamic one, which takes into account the analysis of various parameters, such as the density of vehicles, pedestrian flows, and emergency vehicles. Through the use of a robust analysis of all these parameters, the technology works towards preventing stop-and-go behaviors that lead to high levels of pollution in cities. The study found that their model is able to reduce average vehicle waiting time by 30%, while reducing the fuel usage at the intersections by 25%.

Research Gaps

Despite many successful advancements observed in the above researches, there are still some serious shortcomings in the field of artificial intelligence for traffic management systems. First of all, almost all of today's technologies are reactive, making a decision about changing the signaling regime solely based on vehicle numbers or density at certain points, but not predicting the traffic congestion in the future through advanced time series methods such as Long Short-Term Memory (LSTM). Secondly, even though some individual solutions show promising results in recognizing objects (YOLO) and/or calculating their speed, they do not provide the opportunity to aggregate data into an interactive model "Digital Twin" that could be simulated in real-time at any moment of time and used by the city planners to improve traffic conditions. Finally, many solutions forget about the practicability of deploying the system in the mixed environment, where the pedestrian safety and priority of emergency vehicles need to be considered, as well as collecting and storing data in web portals.

III. METHODOLOGY

AI-based Digital Twin Framework for Quantum Optimized Smart Traffic Analysis & Control is developed as a multi-step method that includes computer vision, deep learning, estimation of traffic density, prediction, quantum optimization, identification of emergency vehicles, and visualization of digital twin. The whole process includes

processing of traffic videos from a four-way intersection to gather the information related to traffic, predict future traffic scenario, optimize signal timing and finally show the results through a Django based web portal. All the steps included in this methodology have been detailed below.

1. Traffic Videos Acquisition and Video Preprocessing

To begin with, traffic videos for all four (North, South, East, and West) directions of a four-way intersection should be acquired. The traffic videos are supplied to the traffic analysis component through the web portal. However, because traffic videos might include noise, poor illumination, lack of contrast, and environmental changes, video pre-processing needs to be done prior to the detection process. The Median Blur algorithm helps eliminate noise while maintaining object borders. Further, Contrast Limited Adaptive Histogram Equalization (CLAHE) technique is implemented to increase local contrast and improve the visibility of vehicles in different lighting conditions.

2. Vehicle detection and classification with YOLOv8

The pre-processed image frames are passed through the YOLOv8 object-detection framework where it detects and classifies the type of vehicles present in the image frames. The different vehicle classes include cars, motorcycles, buses, and trucks. The emergency vehicle detection plays an important role in the traffic management process and is included in this system. Whenever there is an emergency vehicle detected, the data on detection is sent to the alerting and signal controlling module.

3. Multiple Objects Tracking using Byte Track

The detection of YOLOv8 is passed through the multi-object tracking model called Byte Track. It is the task of Byte Track to assign unique identities to the detected cars and maintain the identity over consecutive frames to facilitate the movement of the car, and avoid re-detection of the car. In order to improve detection, NMS (Non Maximum Suppression) is used to eliminate any duplicate and overlapping bounding boxes. Majority Voting is used over consecutive frames to improve the classification of cars. Therefore, the system including YOLOv8 and Byte Track is able to detect, classify, track, and move the car in all four directions.

4. Calculation of Rolling Traffic Density

The data on the vehicles that have been traced is used to measure traffic density for each direction of the intersection. While the number of vehicles at a certain moment of time is not taken into consideration, the system uses rolling traffic density calculation method to analyze the current state of traffic flow during a sequence of frames or intervals of time. The traffic density is calculated separately for each of the North, South, East, and West traffic flows. Depending on the number of cars and traffic density, several levels of traffic condition can be distinguished. The series of traffic density values become the base for traffic prediction and signal adjustment.

5. Future Traffic Prediction via LSTM

The rolling traffic density values are input to a long short-term memory (LSTM) network that is based on the Py Torch library. LSTM is used to find out an dependency in the traffic density values and make a prediction of the future traffic density values. The traffic density prediction values are taken into account as the measure of possible future traffic congestion in each direction. Not just the current traffic density values but future traffic density values can be taken into account by the adaptive control unit as well.

6. Webster's Signal Timing Formula

Before the quantum optimization procedure, the fundamental parameters of the signal timing are computed according to the Webster's formula. Traffic density values are used as inputs for the Long Short-Term Memory (LSTM) neural network which works with the support of the Py Torch library. The reason for using LSTM is to find possible temporal dependencies in the sequence of traffic densities and predict future traffic. Future traffic density prediction is used as a congestion predictor for each direction of the traffic flow. In other words, rather than relying on the traffic conditions at the present time to determine the traffic light timing, the adaptive control algorithm can take into account future traffic conditions as well.

7. QUBO Problem Formulation and QAOA-Based Optimization

The problem of adaptive traffic signal control is expressed as a Quadratic Unconstrained Binary Optimization (QUBO) problem. Traffic density, prediction of traffic, signal phase decision, and timing-related constraints are coded as binary decision variables and objective function. The QUBO problem formulation is then solved using the Quantum Approximate Optimization Algorithm (QAOA). For the QAOA algorithm, the QUBO problem is solved using the Cirq quantum computing package for constructing and simulating the associated quantum circuit. The optimization phase provides signal control decisions according to the objective formulated, helping

the system to explore quantum-based optimization for adaptive signal phases. The decisions, traffic information, and emergency vehicle information will be employed for computing the signal status and allocating the green time to the four directions.

8. Emergency Vehicle Detection and Alert Creation There will be an integration of emergency vehicle detection in the traffic control pipeline to aid priority-based traffic management. Whenever the system detects an emergency vehicle, the emergency vehicle alert message is generated carrying the information regarding the direction and detection. This will facilitate communication of the emergency status to the signal control module as well as incorporation of the emergency vehicle in the digital twin.

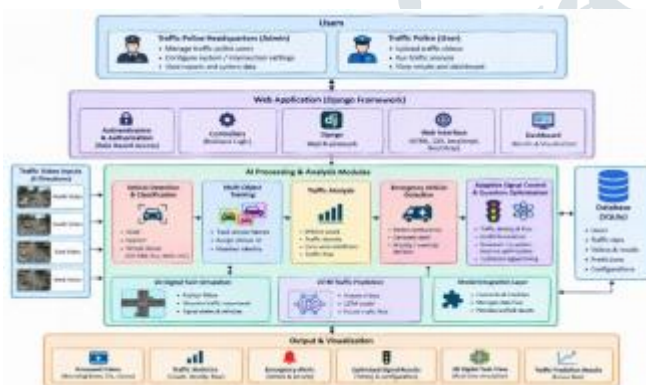
9. 2D Digital Twin Simulation with Pillow

The optimized traffic information is illustrated via a 2D Digital Twin of the four-way intersection. Pillow library in Python is used for creating a visual representation which includes the following – road of the intersection, vehicles, traffic directions, signals, traffic density information, and the status of the signals. The digital twin receives data from the traffic analysis, traffic prediction, traffic emergency detection, and traffic optimization modules. As a result, the modifications in traffic conditions and traffic signal decisions can be visually depicted in the virtual intersection.

10. Django Web Portal and SQLite Database

All the main parts of the system have been incorporated within the web portal created using the Django framework that will act as the interface to run and monitor the proposed system. These include user authentication, upload of videos from four different directions, traffic-analysis results, output videos, density, LSTM predictions, quantum optimization results, emergency alerts, and 2D digital-twin visualization. The SQLite database has been used as the back-end database that can store data such as user information, videos uploaded, traffic analysis results, predictions, signal optimization results, emergency alerts, and others

IV. SYSTEM ARCHITECTURE



V. EXISTING SYSTEM

Most of today's urban traffic control systems have been designed based on a considerable dependency on fixed-time signal controllers, which function according to strictly defined schedules regardless of variations in the actual traffic flow. This is due to the fact that the conventional system of traffic control plans green lights depending on past data, leading to the creation of excessive waiting periods for drivers in the lanes which are not used, while the lanes which are overloaded get too little time to be cleared. In addition, the adaptive systems that make use of sensors (in this case either inductive loop sensors or manual observation systems), also feature high initial costs, limited coverage area, and inability to prioritize emergency traffic or to separate vehicle types.

VI. PROPOSED SYSTEM

In order to address the limitations of the conventional fixed time traffic signal system, an AI-Driven Digital Twin System with Quantum Optimization for Smart Traffic Analysis and Control is introduced by this study. The AI-Driven Digital Twin system with quantum optimization takes videos from the North, South, East, and West sides of the four-way intersection and analyzes them with the help of OpenCV, YOLOv8, and ByteTrack algorithm to

detect and classify vehicles like car, motorbikes, buses, and trucks. In order to increase the quality and reliability of the traffic video analysis process, the techniques of Median Blur, Contrast Limited Adaptive Histogram Equalization (CLAHE), NMS and majority voting have been used. Traffic density estimates are generated continuously by the system, and these time series estimates are fed into the forecasting engine which is implemented using PyTorch's Long Short-Term Memory (LSTM). The predicted traffic data and the live traffic data are then used as input into the adaptive signal control component of the system. The basic traffic signal cycle parameters are estimated using Webster's formula, while the problem of traffic signal optimization is cast as a Quadratic Unconstrained Binary Optimization (QUBO). The QUBO problem is then optimized using the Quantum Approximate Optimization Algorithm (QAOA) implemented via Cirq.

Furthermore, the proposed solution also includes the identification of emergency vehicles and generation of alerts. Thus, the emergency vehicles that are detected are also recognized and accounted for in the process of traffic signals control. The traffic situation, vehicle movement, signals status, density, predictions, and results of optimization are modeled by means of 2D Digital Twin implemented by Pillow Python library. All the above components are included in a secure Django web portal, which is powered by SQLite for database management. The features of the portal include user authentication, uploading of videos, traffic analysis result, output videos processed by the system, LSTM prediction, QUBO-QAOA optimization result, alert for emergency vehicles, and 2D digital twin representation. Through the incorporation of computer vision, deep learning, predictive analysis, quantum optimization, and digital twin technology, the proposed solution offers a comprehensive system for smart traffic management.

VII. RESULT



fig 1 : smart traffic ai login page



fig 2: hq command center



fig 3: 4 way intersection



fig 4: 4 – way video analysis



fig 5: traffic analysis density outputs 4 way

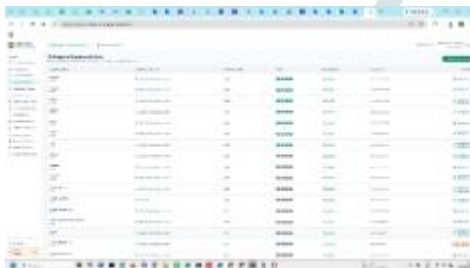


fig 6 : analysis sessions



fig 7 : intersection & roads



fig 8 : adaptive signal control



fig 9 : digital twin 2d twin simulation



fig 10 : emergency vehicle detection



fig 11 : lstm future forecast



fig 12 : reports & csv



fig 13 : traffic police operators

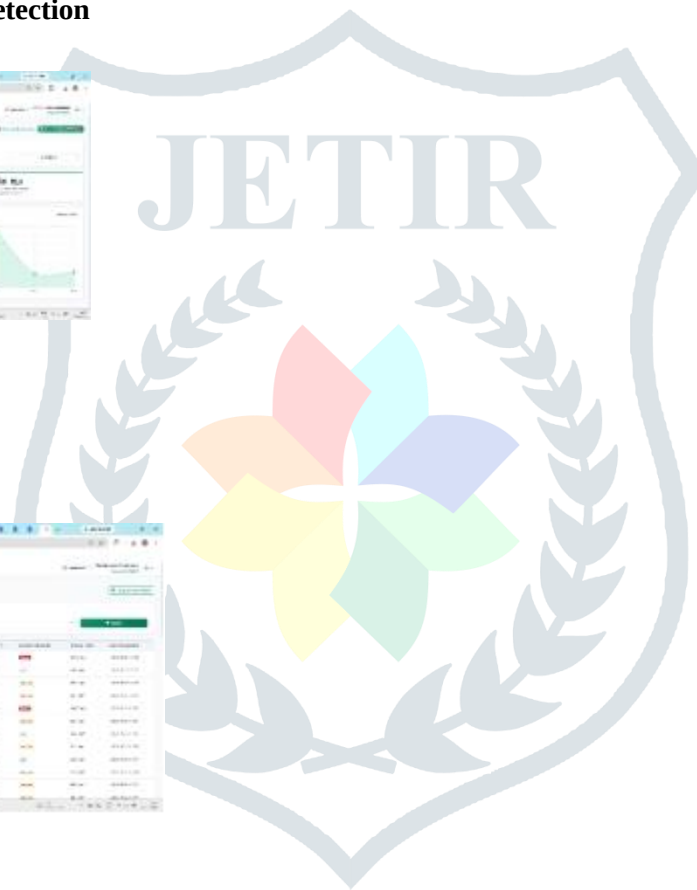




fig 14 : new police operator registration



fig 15 : system & ai model configuration



fig 16 : django database

VIII. CONCLUSION

In light of all the above, the need to manage urban traffic becomes increasingly complicated, and there is a need to move away from the traditional approach to the application of traffic lights. In this regard, this paper proposes an AI-Driven Digital Twin System with Quantum Optimization for Smart Traffic Analysis and Control which applies a set of technologies including computer vision, deep learning, predictive analytics, quantum optimization, and digital twin in order to manage four-way intersections. The use of YOLOv8 and ByteTrack provides for real-time detection, classification, and tracking of multiple objects in the North, South, East, and West directions. The use of rolling traffic density calculation along with the PyTorch implementation of LSTM makes it possible to predict future traffic scenarios by analyzing the historical data. The parameters for signal timing will be provided by Webster's formula, whereas the formulation of signal control as the QUBO problem and its solving via QAOA using the Cirq package will allow the system to have a quantum solution to the adaptive signal phase optimization problem. The inclusion of the module for detecting emergency vehicles and sending out alerts is also provided. The Pillow-based 2D Digital Twin offers a visual depiction of the intersection, incorporating vehicles movement, traffic volume, signals status, and control decisions optimizations. In addition, the Django-based web portal along with SQLite database is designed to offer an integrated environment for authentication, video processing, traffic analysis outcomes, forecasts, optimization outcomes, emergency notifications, and visualization of the digital twin. With the help of these technologies, the proposed architecture offers an integrated solution for traffic monitoring in real time, traffic forecast in the future, adaptive signals optimization, and virtual traffic simulation. The implemented system serves as a base for further studies and practical application of ITS and smart cities traffic management solutions.

IX. FUTURE SCOPE

While the discussed solution exhibits high competence in combining computer vision, predictive analysis, quantum computing, and digital twins for an isolated four-way intersection, there are multiple areas that can help improve its performance and scalability. The future work direction will involve scaling the proposed architecture from a single node to a multi-intersection network in order to synchronize global corridors' traffic signals and implement the green wave. As far as computation is concerned, switching from quantum simulators to Quantum Processing Units (QPUs) will provide the opportunity for QUBO-QAOA pipeline to work with bigger and higher-dimensional state spaces. To reduce video transfer latency, YOLOv8 and ByteTrack inference algorithms will be moved to edge computing resources like NVIDIA Jetson products situated at the signal poles. Moreover, C-V2X feeds will be added to complement video-based telemetry in case of adverse weather conditions, while a transition from 2D visualization to 3D WebGL digital twin coupled with a distributed time series database (such as PostgreSQL with PostGIS) will ensure.

X. REFERENCES

- [1] Ghosh, S., Saha, T., Biswas, D., Pal, D. R., Shil, M. C., & Debbarma, B. (2025). AI-Powered Smart Traffic Management System for Urban Congestion Reduction. *International Journal of Computer Techniques (IJCT)*, 12(5), 413-418.
- [2] Sourav, S., Alam, S. K. M., Dhiman, A., & Singh, A. (2026). AI-Based Traffic Control System: An Intelligent Approach to Urban Traffic Management using Computer Vision and Deep Learning. *International Journal of Engineering Research & Technology (IJERT)*, 15(3).
- [3] Sasikala, D., Sakthivel, G., Sivachandiran, R., & Suriyabhuvanesh, E. (2025). AI-Based Smart Traffic Signal Control System. *International Journal of Research Publication and Reviews (IJRPR)*, 6(4), 10640-10642.
- [4] Reddy, L. K., & Sree, K. S. (2024). AI-Based Traffic Management System. *International Journal of Creative Research Thoughts (IJCRT)*, 12(6), j444-j450.
- [5] Kadam, M., Sutar, A. U., Kakad, V. V., Dubale, S. A., & Vaidya, S. S. (2025). Traffic Management Using Artificial Intelligence. *International Journal of Novel Research and Development (IJNRD)*, 10(6), a192-a196.
- [6] Rani, K. S., Haniya, S. K., Hafizunnisa, S. K., Reddy, P. V. S., Kumar, P. V., & Prathyusha, K. (2024). Traffic Congestion Control through Adaptive Signaling System using Machine Learning. *International Research Journal of Engineering and Technology (IRJET)*, 11(3), 1255-1261.
- [7] Nandhini, S., Kumar, M. R. M., Mownika, M., Ranganayagi, K., & Pavithra, R. J. (2025). Smart Traffic Surveillance System with Adaptive Traffic Control Signal using YOLO. *International Journal of Engineering Research & Technology (IJERT)*, 13(5).
- [8] Genitha, C. H., Danny, S. A., Ajibah, A. S. H., Aravint, S., & Sweetty, A. A. V. (2023). AI based Real-Time Traffic Signal Control System using Machine Learning. *Proceedings of the Fourth International Conference on Electronics and Sustainable Communication Systems (ICESC-2023)*, 1613-1618.
- [9] Bosco, S. L., Anselm, A. K., & Manikandan, G. (2026). AI based Traffic Detection and Management System. *2026 Contemporary Computing Innovations Conference (CCIC)*.
- [10] Sharma, C., Panigrahy, S. K., & Reeya, S. R. (2025). AI-Powered Solutions for Safer Driving: Traffic Forecasting and Dynamic Signal Control Using LSTM. *2025 5th International Conference on Artificial Intelligence and Signal Processing (AISP)*.
- [11] S. Agrawal, R. Sharma, P. Srivastava, and V. Patel, "Adaptive Traffic Signal Control System Using Deep Reinforcement Learning," in *2024 IEEE International Conference on Intelligent Signal Processing and Effective Communication Technologies (INSPECT)*, 2024, doi: 10.1109/INSPECT63485.2024.10896157.
- [12] Ge, Y., & Qin, Y., "Digital Twin Intelligent Transportation System (DT-ITS): A Systematic Review," *IET Intelligent Transport Systems*, 2024.
- [13] Zhang, Y., Sun, P., Jiang, Y., Yu, D., Weng, F., Yuan, Z., Luo, P., Liu, W., & Wang, X., "ByteTrack: Multi-Object Tracking by Associating Every Detection Box," *European Conference on Computer Vision (ECCV)*, 2022.
- [14] Jocher, G., Chaurasia, A., & Qiu, J., "Ultralytics YOLO," *Ultralytics*, 2023–2024.

- [15] Ma, X., Tao, Z., Wang, Y., Yu, H., & Wang, Y., “Long Short-Term Memory Neural Network for Traffic Speed Prediction Using Remote Microwave Sensor Data,” *Transportation Research Part C: Emerging Technologies*, 2015.
- [16] Ma, X., Tao, Z., Wang, Y., Yu, H., & Wang, Y., “Long Short-Term Memory Recurrent Neural Network for Traffic Flow Prediction,” *IEEE International Conference on Intelligent Transportation Systems*, 2015.
- [17] Inoue, D., Okada, A., Matsumoto, M., et al., “Traffic Signal Optimization on a Square Lattice with Quantum Annealing,” *Scientific Reports*, 2021.
- [18] Sutton, R. S., & Barto, A. G., *Reinforcement Learning: An Introduction*, 2nd Edition, MIT Press, 2018.
- [19] Haydari, A., & Yılmaz, A., “Deep Reinforcement Learning for Intelligent Transportation Systems: A Survey,” *IEEE Transactions on Intelligent Transportation Systems*, 2022.
- [20] Wei, H., Zheng, G., Yao, H., & Li, Z., “IntelliLight: A Reinforcement Learning Approach for Intelligent Traffic Light Control,” *Proceedings of the 24th ACM SIGKDD International Conference on Knowledge Discovery & Data Mining*, 2018.
- [21] Vaswani, A., Shazeer, N., Parmar, N., et al., “Attention Is All You Need,” *Advances in Neural Information Processing Systems (NeurIPS)*, 2017.

