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Intelligent Signal Management for Bidirectional Traffic using Vehicle Density Evaluation

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***Abstract*— The congestion caused by the inefficiency of the fixed-time systems of traffic lights is critical at the urban road intersections, and they cannot adapt to the changes in vehicle density. This causes the wastage of time in unnecessary waiting, consumption of fuel and emergency delays. The proposed system of intelligent two-way traffic control with the use of ultrasonic sensors to dynamically assess the real-time vehicle density at the signal points will resolve the limitation. The arduino Mega 2560 gathers and continuous distance readings and prioritizes switching of signals according to the real presence of traffic. It goes around vacant lanes automatically and halts on the existing signal during an all-vacant situation of the roads. The main goal in this case is the minimization of idle signal time and automation of the traffic throughput. It is novel in that it has a real-time adaptive skipping logic, in contrast with the traditional cyclic systems; though does not contain any redundant delays, contrived to ensure responsiveness at zero traffic rates. This offers an economically viable, hardware-friendly and an autonomous complete smart traffic management system.**

***Keywords*— Intelligent Traffic Control, Vehicle Density Monitoring, Adaptive Signal Management, Congestion Reduction, Smart City Infrastructure, Real-Time Decision Making, Automated Traffic Optimization.**

I. INTRODUCTION

Traffic congestion on the urban road network through the increased number of vehicles on the road place a tremendous burden on traditional traffic management operations in the urban transport systems. The conventional traffic light controllers used are of a fixed time basis; they have a certain amount of time allocated to each signal regardless of the availability of vehicles or not. This makes [1] very inefficient in times when there are non-peak periods or times of an emergency where other lanes are unevenly endowed by the traffic. Owing to this, commuters are often exposed to trafficking at crossroads with no traffic, which is frustrating, consuming too much fuel, air pollution and wastage of valuable time. The inefficiencies demonstrate the weaknesses of the existing, non-adaptive, traffic control systems, and promote the necessity to work with the intelligent, adaptive technologies, which can be introduced to make the real-time decisions in the optimization of the traffic flow in cities.

Traffic situations in urban environments are alternating within only a few seconds, and even a lack of their response in seconds leads to a chain reaction of congestion. Human operated systems tend to be unsatisfactory because of slow decision making, distraction or manual discrepancy. Automated fixed timers although good in performance [2] are the worst in intelligence.

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They do not differentiate the lanes of traffic irrespective of the density and therefore lead to the development of vehicle queue in the high density lanes whilst vehicles in the low density or empty lanes must wait in vain. Such blanket manner of approach is quite naive because real-time traffic is not smooth and even, particularly in non-peak timings, at odd hours like late nights, during periods of festivals, during rains, or emergency response exercises.

Thus, there is a great necessity in smart traffic light systems which can analyze the real road situation and adjust the timing of the signals at any moment and not according to a circular order, blindly [3]. These gaps have been filled in the proposed intelligent signal management system which incorporates ultrasonic sensors to check vehicle density in real time. According to an ultrasonic wave reflection, these sensors are able to detect the presence or absence of a vehicle, by calculating distance. When it identifies any vehicle in a specific range it identifies that specific lane as an active one and gives it a priority in the traffic signal.

In the situation where there is no vehicle detected then the vehicle smartly avoids that lane rather than wasting time on the unnecessary stage of a signal. This system makes sure that only lanes that have traffic are given access even though empty roads are automatically disregarded. In addition [4], in case all the four signals occur to be unoccupied, then it cleverly holds onto the signal, and waits to record a traffic in any direction. The point is not to waste time on meaningless circular riding and to save money and time on power and timing resources. The technique uses low-priced, readily available hardware parts, such as the Arduino Mega 2560 and HC-SR04 ultrasonic sensors, to render it feasible to use it in developing areas.

As the logic of making decisions is a purely logical algorithm instead of a computation-intensive one, its execution requires a fast time with insignificant processing delay. The system has been modeled after what a human traffic officer would accomplish when it comes to dynamically deciding whether a switch of signals is necessary or not [5] based on the real vehicle presence, with the difference that it rules out the human factor and ensures immediate responsiveness. It is more adaptive hence better throughput, and waiting time is very low during heavy loads at night or in light loads when timers are most inefficient. This guarantees direct cuts on the use of fuel, decrease in carbon emissions, easier accessibility in case of an emergency, and generally have a smoother vehicle movement.

This model in addition to being efficient is also very scalable. In future on the same logic, addition of additional lanes or emergency vehicle preference priority can be added. It may also serve as an entry point to any smart infrastructure city in which smart transport networks make communication [6] with other infrastructure. Lastly, this system is an effective and feasible advancement towards intelligent traffic automation of the future, and shows that relatively simple but smart sensing logic can perform better than old-fashioned traffic signal systems because it responds in real time to the ever-changing city mobility behavior.

This paper will be organized as follows where literature survey review is presented in Section II. Section III describes the methodology, including paying particular attention to its operationality. In Section IV is the result and discussions. Lastly, the last section is V, that contains the final findings and recommendations.

II. Literature Survey

This study on intelligent road management represents a progression of operation of the fixed time signaling systems to adaptive and sensor-based methods that can respond to actual changes in the traffic in real-time. The initial studies in the field were based on manual control and cyclic models of time that were effective mainly with homogenous flows of traffic. Subsequent studies came up with the use of automated sensing devices such as infrared, camera vision, and ultrasonic technology in detecting the density of live vehicles and signal switch to maximize. Those RFs that have appeared recently are focused on artificial intelligence, the right to be connected, as well as integration with smart infrastructure. Such works are explored in this survey, and they are examined based on their efficiency, constraints, and appropriateness in designing an autonomous traffic control solution that is cost-effective.

Congestion in cities generates disordered trends of motor traffic flow and vagaries in transportation. This literature dwells on the dynamic adaptation of the fast varying signal actions and uncertain communication between junctions in real time, through the controllable state transitions which reflect the prevalent signal decisions. It is prioritized with scalability between several intersections and with respect to failures [7]. In fact, the findings suggest the decrease of the short-term traffic conditions awareness deficit, the decrease of the imbalance between approaches, and increases in the belief towards the continuous citywide operation. It can therefore better adjust to changing densities in complex junction plans, which change rapidly. The net effect is more useful traffic information to aid IMRT routing and easier flows through various conditions even in absence of special infrastructure and external recalibration.

This is a case where, in peak seasons, the demand on the motorways habitually overpowers the space used on the roads. Rather than constructing lanes, this project literally resettles the use of width to ensure roadside area that is not used can be used as passageway in case of reduced speeds. Capacity is enhanced early enough before the problem of congestion arises. Spatial flexibility is considered to be a configurable operational resource [8], infrastructure layout and traffic control in real-time. Timings of their execution are planned around surges of demands. On various expressways, simulations result in shorter delay periods, more evenly distributed across the number of lanes as well as the utilization of lateral distance that is not in use currently. Firm changeability over broad demands patterns is exhibited under protected operation limits.

Big road networks are two of the characteristics of large road networks: uneven distribution of intersection significance and strategic battles. Computationally it is difficult to solve all things simultaneously. In the work, the control decisions are broken down into two connected layers of hierarchy with the crucial locations determining the peripheral ones. Cooperation [9] and competition in the sub-regions within the network ensure the avoidance of bottleneck escalation. It is solution-wise that it first solves influential intersections, and then coordinates followers to avoid conflicting decisions. The preceding results indicate that it takes less time to travel, the average speed is finally higher, and also less conflict at junctions. In the big city plans, learning and convergence are far more predictable. In general this method mitigates reactive chaos, and provides almost globally synchronized signals timing in intricate connected city grids.

This paper explores the ability of adaptive strategies of regulating an intersection within a city to respond to sudden, unforeseen disruptions. Though most of these approaches have been found to promise a lot to the stable traffic, little information is available on how they would perform when there is a disruption. Test conditions bring about irregular bursts and abnormal scenarios [10] not experienced in the previous training or tuning. Comparative experiments are done exploring the way each mode of operation maintains flow, avoids cascading delay, or comes back after surprises in density. Certain strategies have a strong natural look and they self-organize whereas others degrade and over -reaction. This paper indicates a number of issues regarding real world reliability as well as stating that upfront resilience and self-stabilizing ability is paramount instead of average congestion capability.

Due to the expansion of population and greater use of individual transportation, it brings about urban overcrowding. An analog clock tends not to refresh the dynamically shifting densities in the real-time, due to the imbalanced queues. The publication utilizes the current traffic situation straight off the map. It aims at being fair between the approaches [11], whereas still giving preference to busier ones in the critical times. The continuous adaptation of the greater green sharing is carried out.

The results of simulation shows much improvement over delays, length of queue and the experience of travel when comparing with the older methods. The higher throughput is more responsive to changeable patterns to be observed in the repeated simulations, contributing to a fluent travel and a more independent movement of networks in the city without large hardware extensions.

This trade-off of the urban centers should be between the normal day-to-day mobility and passing through emergency vehicles with as little obstruction as possible. Traditional schedules pay little attention to urgent passages or cannot afford the high throughput to normal users. This paper presents a concept which monitors the real time traffic and integrates emergency awareness [12] to expedite priority traffic. During operation at live, communication infrastructure is configured to be reliable and fast. The assessments are also reporting a reduction in general waiting, better long-term adaptability, and faster emergency clearance. Everyday trips are as well as critical incidents. Provides more balanced daily operation under congestion variations in density multi-junction solutions and covers more of the dense multi-junction areas.

Existing urban traffic modelling is inadequate in the portrayal of daily complications of growing metropolitan circulation. This survey analyzes the current trends that capitalize on the large data presence to achieve more sensible and flexible simulations. The paper presents pragmatic results, significant strengths, and also gives a revelation of difficulties like data acquisition, transferability [13], and real world alignment. This is provided in a basic case example that illustrates adaptive learning can help decrease waiting time by a considerable margin as opposed to the control situation. Code availability promotes wider adoption and imitation. It can be expected that future opportunities to fill the remaining divisions between virtual representation and lived conditions, expand them past central cores, or enhance interpretability by city authorities.

This paper examines the application of large-scale sensor implementations to provide real-time traffic data, which can be used to furnish ongoing predictions that can be applied to meet the contemporary smart city demands. Interactions between roads at a spatial level are estimated and honed to generate more accurate forward predictions [14]. Swarming optimization method optimizes decision behavior to make it more responsive to varying demand. Through experimentation, a considerable decline in delays has been established without compromising system responsiveness to an extent that makes it usable by people in their day-to-day activities. The method can be used to take timely corrective measures, it has a strong scalability and is compatible with the existing infrastructure. Its findings demonstrate that the anticipatory logic method can decrease congestions within grids of size and complexities to facilitate more secure mobility and more positive experiences by users in real time.

The vehicle behaviour at urban crossings must be cognizant of the one heading in many directions as well as distances otherwise there is a likelihood of overserving one of the approaches to the disadvantage of the other. The work makes the controller more sensitive to the incoming traffic, highlighting the key features [15] in such a manner that the quality of decision-making should be better. It is dynamically changed to reflect the needs of each direction instead of rotating regularly. It is demonstrated that the evaluations work out with a shorter delay, the reduction of stops, and the minimization of the formation of queues compared to the previous generation of adaptive systems.

There can be difficulties with synchronizing various junctions in real time due to the significant change of inflow volumes which are quite often different, varying turns of movements, and dynamic preferences of the users. This piece of work promotes collaboration between junctions to prevent potential conflict of solitude in individual decisions. Awareness of density in each approach is based on visual traffic information. Intersection [16] also considers the signals of its neighbor in an effort to predict possible spillovers. There are realistic camera input and realistic traffic experiments. The system can continuously eliminate waiting which levels off the peaks. It is constructed to extend over a number of interconnected junctions. It aims at providing smoother progression of the corridors and preventing sudden local interventions that can disrupt downstream or upstream strategies. Intersections on the cities are usually based on preset time, which does not consider congestion at present.

It uses a vision-based configuration that identifies the existence of the vehicle directly using live camera feed. It also instantly controls the timing of movement based on the density being observed. Closely co-located cross roads share context, one queuing with another being over-utilized [17]. When there is a need, high-stakes locations like hospitals or schools are given priority. The strategy reduces overhead in signal reconfigurations as well as network traffic.

Assessment of this reveals significant changes in waiting time wastage and congestion. In practice, it is preferable to a more cost effective implementation which is acceptable as a supplementary layer to the overall methods of city design by the next generation to be safer and smoother mobility. Intercity highways are generally marred with frequent slowups which are unwelcoming to travel time and reliability.

This paper gives a control plan, which converts readings of speed and flow into independent ways of working, which distinguish between jammed and non-jammed states. A structured decision layer evaluates the existing density and understands general congestion level. This does not entail huge historical books. Experimental results [18] indicate stable conformity with the forecasted traffics. The method is applicable to different highway density without an elaborate calibration. Chaining of many of them can be made to anticipate longer distances. Its short-memory nature enables quick response to events and aids in dealing with congestion preemptively as well as influences the course of action by the management through few computations. Large amount of data has needed to be collected in intersection performance assessment.

This work also engages the use of rudimentary arrival and departure counts using passive detecters to display real time approximations of total delays. It is non-creative in that it follows an approach that estimates accumulation of vehicles within the junction limits with balancing counted inflows and outflows [19], and without the incurred expensive manual reporting.

Problems of varying complexity of the networks are resolved. It is found that when compared to known simulation results, there is a stable reliability of the comparison with both light and saturated volume. The strategy enables future integrations into an adaptive environment or more broad coordination systems. Created to be field practical, it makes agile paradigm monitoring and active intervention decisions in day to day operations in the city.

Cities having large populations may enjoy the advantages of region-based flow balancing that manifests in the total circulation of the network not surpassing the critical levels of network congestion. This art considers the boundary of every urban area as a regulated entrance. It determines the amount of flow that can safely be in or out of each region in order to maintain preferable densities. This is then followed by signal-time adjustments [20] at intersection of boundaries. When testable in a real city, it is found that mobility performance is significantly better than that of doing nothing or having an immediate reaction. Traffic congestions cut across all sub regions. This one improves performance of complete corridors and is not specific to the optimization of individual blocks providing close opportunities of systemwide coordination on a larger scale.

III. METHODOLOGY

The proposed system operates vehicle detection in real time being an alternative to conventional variable switching which is time-based. Arduino Mega 2560 is the primary control unit that reads live distance data constantly using ultrasonic sensors mounted at every signal point in the four lanes and thus gives a resolution as to whether or not there is traffic in the lane. Instead of rotating the state of the traffic lights in a blind manner, it is updated dynamically based on the priority and availability. The intelligent design will make sure that the activation of signals is performed only when vehicles are present. It avoids the unnecessary delays and minimized idle wait times and also provides energy-efficient congestion-aware traffic flow control with no human involvement.

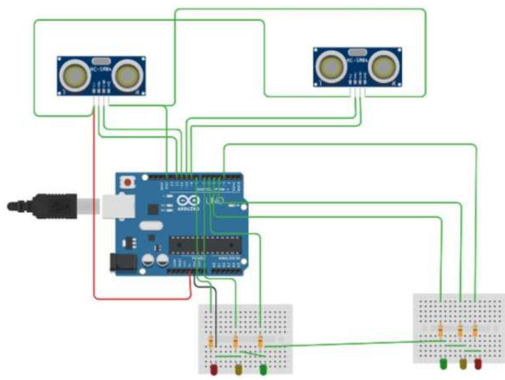

Fig. 1. Circuit diagram

A. System Initialization

This begins with the configuration of all hardware as well as the assignment of appropriate roles to each connection. The four HC-SR04 ultrasonic sensors will lastly be polled to predefined new trigger and echo pins in the Arduino. Meanwhile, the red, yellow and green indicators of each signal are set as output pins to limit the damage through resistors. All the signals are initialized in a safe default state, which normally places all the red LEDs on. At this stage, initial threshold values of a car are established, they allow the controller to determine whether a lane is occupied upon tracking live distance measurement.

B. Distance Measurement

The ultrasonic sensors produce high frequency sound pulses of continuous type through their trigger pins. A pulse of very small duration is emitted and the corresponding echo pin waits till the reflected wave of the sound produced by any vehicle that is in range is detected. This is done by recording the amount of time (innumber of microseconds) which the Arduino requires to record the pulse in response. This time taking the speed of sound which was already known, is made as distance. The calculations are cyclic and this way enables continuous sensing. These measurements of values are updated in real time and are used to establish the values required to detect accurately the lanes occupied and thus make a decision on the intelligent operation of the traffic lights.

C. Vehicle Density Evaluation

The predetermined threshold used to determine the logic of vehicle presence is compared with the measured distance value of each sensor. When the measured distance is below this value, this will be a surety that one or more vehicles are waiting in the signal. When the value is more, it implies that the lane is empty. The step entails transformation of raw distance data into valuable traffic status information. All the four signals will remain alive on Arduino. The key idea in this classification is that the system is able to determine which signal should be triggered, bypassed, or suspended to ensure that time is not wasted by the system on empty lanes.

D. Decision-Making Algorithm

The controller then evaluates each signal, and the assessment of the signals based on the lane status is determining the most appropriate next signal to turn on. The system takes a standard rotation order in case there are cars in all lanes. When there are empty lanes, then the lanes are immediately skipped so that there are no delays. When lanes are vacant the controller retains the current signal and does not clear till traffic appears at other locations. This smart reasoning enables dynamic responsiveness instead of predetermined schedules; hence, it is destroying the green lights which lie during non-traffic and streamlines the traffic in every direction.

E. Signal Control Logic

Once the target signal is selected, the system resumes the output LEDs as follows, the selected signal is passable and its green LED is turned on whilst the rest remain all red. The system temporarily activates the yellow LED at the expiration of the permitted passage time in order to indicate a safe passage. The green LED is switched off, and the next available signal is switched on once again on the basis of new sensor assessment. This ensures that it has a safe, easy and rational traffic switching process, within regular light signaling principles whilst remaining dynamic and traffic-sensitive in real-time.

F. Continuous Operation and Feedback

The entire process is a continuous circle whereby the processing of the live traffic conditions is never to be stopped. Once one iteration has been run, Arduino automatically reads all ultrasonic sensors again and reconsiders the lane availability and comes to the following decision. Such a feedback mechanism will allow to have a direct response in case of a sudden emergence or vanishing of the traffic. There will be no requirement of using timers or manual control once it is turned on because it will run in a loop and correct the situation automatically when it is under most of the conditions of real-world conditions to be considered to pass the traffic safely without any congestion and idle signal time of all the four directions.

IV. RESULT AND DISCUSSION

The smart traffic signal control framework demonstrated quite an effective performance in real-time flexibility and responsiveness to the actual existence of a vehicle. The system was not provided to work under a fixed rotation sequence but rather signal changes were to be executed after it is detected that there is a vehicle present. It was therefore able to alleviate significantly the idle signal delays, as they did not spend any time letting empty lanes pass. Consistency in the transitions between green-yellow-red was very smooth and well-timed as the clearance between the direction changes was significantly calculated without the sudden suspicious stop and twinkling. The overrun was comparable to the traits and feature of contemporary traffic adaptive systems, and therefore was largely fit to operate in unpredictable urban conditions, devoid of manual controls and time configurations beforehand.
When it comes to the implementation of an immediate control response and the decision logic of high precision, during the observation in the changing availability of vehicles, when it suddenly appeared in the traffic flow in an excessively extensive number, the corresponding lane was prioritized without the need to wait until the redundant countdown. The system avoided unnecessary switching congestion and hence unnecessary illumination in case intermittent arrival of vehicles occurred. Times that tend to define traditional infrastructures based on time. The clearance time of vehicles was evidently optimized to enhance the road throughput by its responsiveness. There was no subjective feeling of latency in detection and action. The system carried out every activity independently and kept on recalculating the priority and that too in realtime which proved the design goal of the use of intelligence rather than hard coded logic. The switching was stable and perfectly synchronized even when there were sudden shifts in the direction of the traffic of the vehicles.

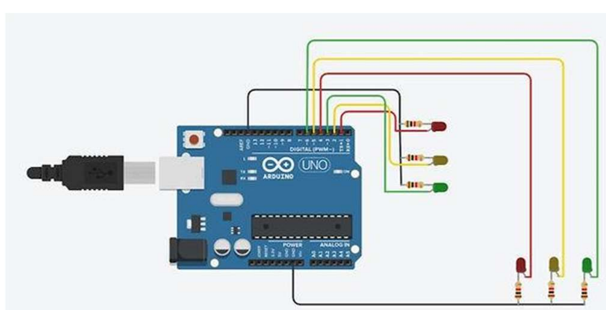

Fig. 2. Arduino with LED

The system in cases where there were no vehicles that remained long without vehicles intelligently halted and retained the status at the point, rather than changing to some transition cycles that were unnecessary. Such self-hold action not only ensured that energy was conserved but also it minimized the unneeded operationLED drive, as well as prevented unnecessary signal motion on the road when there was no traffic. This proved the versatility between the opposite conditions by confirming that it not only improved the congested situations, but also the low-traffic conditions by this system. This resulted in inherent power efficiency in that it would only turn on when it is required. The intelligent pause-and-resume mechanism being used therefore contributed a lot into impeding the irrelevant operation cycles.

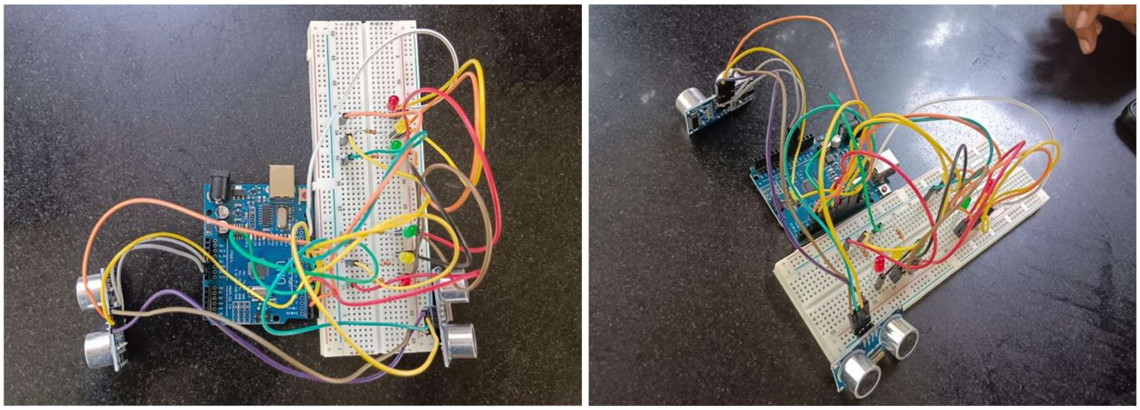

Fig. 3. Proposed Hardware

The accuracy of the sensors was reported to be steady and dependable during the experiment. The actual readings of a distance did not change much when real vehicles fell within the range of detection. The system prevented the misfires of minor motions in the background or open-air reflection, which testifies that the combination of the sensors is strong.

Commissions were never made on short term fluctuations but rather debated information. The real-time algorithm ensured that even the presence of single vehicle was detected in good time, and the appropriate response was provided. Short detection-to-action times also achieved close to zero delay behaviour, an attribute of significance in practical traffic schemes.

To conclude, the autonomous vehicle density assessment reached its intended purpose of intelligent traffic regulation in the system. The system wasted no time on idle conditions and opened way where it was necessary. This decrease in downtime waiting and efficiency improvement in clearance together with the adaptive control response was a solid improvement over the traditional cyclic method. The testing phase confirmed that the methodology is theoretically effective but practically valid with respect to dynamic and uncertain traffic movement. The smart attitude of the supervisor offered optimal flow, low energy wastage, limited non-essential transitions, and demonstrated resilient real-time decision-making capability, and was therefore practical as an effective solution to the contemporary smart transportation infrastructure.

V. CONCLUSION

The suggested intelligent signal management system is sufficient in demonstrating the fact that real-time vehicles detection can enhance the efficiency of traffic flow in a greater way than the traditional fixed-timer signal systems. The system eliminates the unneeded waiting time and is created so that it adapts dynamically, according to the genuine presence of the vehicles, so that the time spent is only where the actual motion is required. Such ability to make adaptive decisions identifies an effective and practical way out in contemporary city traffic conditions which are unpredictable and uneven in demand. Sensor-based logic automation enhances responsiveness, conserves energy and performance overall at an intersection with no human factor involved.

The practical importance of the whole system is associated with the fact that it is appropriate to be used in the real-life implementation of smart city systems when one can observe the varying or uneven traffic density. It is self-optimizing in nature and therefore will perform equally well during high and low traffic conditions and can be used in practice, which has brought about real world usability and usability improvements and will be cheap to install, and therefore can be deployed at scale. Further extensions of the system in the future will involve more complex machine learning models that can potentially predict traffic trends and not just respond to them. The addition of emergency vehicle prioritization to intersection communication by IoT with cloud-based monitoring would significantly increase its smartness, scalability, and coordination on a city-wide scale.

References

[1] M. Kurucan, "Traffic Management System With Symbolic Discrete Controller Synthesis Technique," in IEEE Access, vol. 12, pp. 105393-105402, 2024, doi: 10.1109/ACCESS.2024.3435713.

[2] N. Nigam, D. P. Singh, J. Choudhary and S. Solanki, "An Efficient Model for Real-Time Traffic Density Analysis and Management Using Visual Graph Networks," in IEEE Access, vol. 13, pp. 140413-140439, 2025, doi: 10.1109/ACCESS.2025.3593136.

[3] J. Kang, Y. Choi and K. Sohn, "Simultaneous Optimization of Traffic Signal Control and Vehicle Platooning Scheme Based on Connected and Automated Vehicle (CAV) Technology," in IEEE Access, vol. 13, pp. 99744-99757, 2025, doi: 10.1109/ACCESS.2025.3577165.

[4] Z. Fereidooni, L. A. I. Palesi and P. Nesi, "Multi-Agent Optimizing Traffic Light Signals Using Deep Reinforcement Learning," in IEEE Access, vol. 13, pp. 106974-106988, 2025, doi: 10.1109/ACCESS.2025.3578518.

[5] P. Bindzar, D. Marasova, J. Brodny, M. Tutak, R. Ulewicz and A. Sliva, "Modeling the Impact of Intersection Design Configurations on Traffic Flow During Peak Hour in Smart Cities: A Case Study on Urban Roads in Slovakia," in IEEE Access, vol. 12, pp. 83072-83090, 2024, doi: 10.1109/ACCESS.2024.3412709.

[6] E. Ei Mon, H. Ochiai and C. Aswakul, "Application of Traffic Light Control in Oversaturated Urban Network Using Multi-Agent Deep

[7] Reinforcement Learning," in IEEE Access, vol. 12, pp. 82384-82395, 2024, doi: 10.1109/ACCESS.2024.3397495.

[8] Y. H. Taher et al., "Filter for Traffic Congestion Prediction: Leveraging Traffic Control Signal Actions for Dynamic State Estimation," in IEEE Access, vol. 13, pp. 8140-8157, 2025, doi: 10.1109/ACCESS.2024.3525119.

[9] M. Rostami-Shahrbabaki, M. Keyvan-Ekbatani, K. Bogenberger and M. Papageorgiou, "Dynamic Lane Configuration for Improved Traffic Efficiency on Motorways," in IEEE Transactions on Intelligent Transportation Systems, doi: 10.1109/TITS.2025.3592304.

[10] H. Shen, H. Zhao, Z. Zhang, X. Yang, Y. Song and X. Liu, "Network-Wide Traffic Signal Control Based on MARL With Hierarchical Nash-Stackelberg Game Model," in IEEE Access, vol. 11, pp. 145085-145100, 2023, doi: 10.1109/ACCESS.2023.3345448.

[11] M. Korecki, D. Dailisan and D. Helbing, "How Well Do Reinforcement Learning Approaches Cope With Disruptions? The Case of Traffic Signal Control," in IEEE Access, vol. 11, pp. 36504-36515, 2023, doi: 10.1109/ACCESS.2023.3266644.

[12] K. Sreejith, S. Mathi and P. Pradeep, "Beyond Sensors: IntelliSignal's Map-Integrated Intelligence in Traffic Flow Optimization," in IEEE Access, vol. 12, pp. 39028-39040, 2024, doi: 10.1109/ACCESS.2024.3375335.

[13] O. S. Al-Heety et al., "Traffic Congestion Control with Emergency Awareness and Optimized Communication Infrastructure using Reinforcement Learning and Non-Dominated Sorting Genetic Algorithm," in IEEE Access, doi: 10.1109/ACCESS.2025.3530243.

[14] H. Maheshwari, L. Yang and R. W. Pazzi, "Machine Learning Advancements in Urban Traffic Simulation: A Comprehensive Survey," in IEEE Open Journal of Intelligent Transportation Systems, vol. 6, pp. 1027-1052, 2025, doi: 10.1109/OJITS.2025.3589208.

[15] Z. Miao and Q. Liao, "IoT-Based Traffic Prediction for Smart Cities," in IEEE Access, vol. 13, pp. 52369-52384, 2025, doi: 10.1109/ACCESS.2025.3552276.

[16] P. Wang and W. Ni, "An Enhanced Dueling Double Deep Q-Network With Convolutional Block Attention Module for Traffic Signal Optimization in Deep Reinforcement Learning," in IEEE Access, vol. 12, pp. 44224-44232, 2024, doi: 10.1109/ACCESS.2024.3380454.

[17] M. A. Hassan, M. Elhadef and M. U. G. Khan, "Collaborative Traffic Signal Automation Using Deep Q-Learning," in IEEE Access, vol. 11, pp. 136015-136032, 2023, doi: 10.1109/ACCESS.2023.3331317.

[18] A. Hazarika, N. Choudhury, M. M. Nasralla, S. B. A. Khattak and I. U. Rehman, "Edge ML Technique for Smart Traffic Management in Intelligent Transportation Systems," in IEEE Access, vol. 12, pp. 25443-25458, 2024, doi: 10.1109/ACCESS.2024.3365930.

[19] M. -J. Hao and B. -Y. Hsieh, "Greenshields Model-Based Fuzzy System for Predicting Traffic Congestion on Highways," in IEEE Access, vol. 12, pp. 115868-115882, 2024, doi: 10.1109/ACCESS.2024.3446843.

[20] A. Almutairi, P. Yi and M. Owais, "New Approach for Estimating Intersection Control Delay From Passive Traffic Sensors at Network Level," in IEEE Access, vol. 12, pp. 2882-2900, 2024, doi: 10.1109/ACCESS.2024.3349499.

[21] Y. Ma and Z. Liu, "Optimal Perimeter Control for Multi-Region Traffic Networks Based on Macroscopic Fundamental Diagram," in IEEE Access, vol. 12, pp. 61937-61948, 2024, doi: 10.1109/ACCESS.2024.3394717.