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Research Paper

An Embedded Lane-State Morphing Framework for Adaptive Vehicular Flow Equilibration in Multi-Directional Traffic Environments

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ABSTRACT

Urban traffic congestion has become a major challenge in modern smart cities due to the rapid increase in vehicle population, resulting in excessive travel delays, fuel wastage, environmental pollution, and road accidents. Traditional traffic management systems mainly depend on fixed lane dividers and static traffic signal mechanisms that cannot adapt to real-time fluctuations in traffic density between opposite road directions. During peak hours or special events, one side of the road often experiences severe congestion while the opposite lane remains underutilized, leading to inefficient road capacity management. These limitations highlight the need for an intelligent and adaptive traffic control system capable of dynamically balancing traffic flow. To address this issue, the proposed IoT (Internet of Things)-enabled Automated Moving Divider for Dynamic Traffic Flow Control system introduces a smart sensor-based movable lane divider that automatically adjusts lane allocation according to live traffic conditions. The system integrates an ESP32 (Espressif 32) microcontroller, IR (Infrared) sensors for bidirectional vehicle density monitoring, a DC (Direct Current) motor for divider movement, an LCD (Liquid Crystal Display) for status visualization, a buzzer for alert notifications, and an IoT communication module for remote monitoring and supervision. Based on real-time sensor data, the ESP32 intelligently controls divider positioning to optimize road utilization and improve traffic distribution. The proposed system significantly enhances traffic throughput, reduces congestion, minimizes fuel consumption and emissions, and supports efficient, automated urban traffic management without human intervention.

Keywords: IoT, Traffic Management, Automated Lane Divider, ESP32, DC Motor, IR Sensor, Smart Traffic Control, Dynamic Lane Allocation, Embedded Systems, Real-Time Monitoring

1. INTRODUCTION

The rapid transformation of urban environments, accompanied by the continuous increase in vehicle ownership and population density, has significantly intensified transportation-related challenges in cities worldwide. Modern road infrastructures frequently struggle to accommodate fluctuating vehicular movement patterns, particularly during office peak hours, festival seasons, emergency evacuations, road maintenance activities, and large public gatherings. In many situations, traffic flow becomes heavily concentrated in one direction while the opposite carriageway experiences comparatively lighter usage, resulting in severe traffic bottlenecks, prolonged commuter delays, excessive fuel consumption, elevated carbon emissions, and increased risk of roadway incidents. Existing traffic regulation approaches primarily rely on permanently installed lane dividers, static lane assignments, and conventional signaling mechanisms that lack the adaptability required to respond dynamically to continuously changing transportation demands. Because of this inflexibility, a considerable portion of available road infrastructure remains underutilized, reducing overall transportation efficiency and negatively impacting economic productivity and public mobility.

Recent advancements in smart transportation technologies and connected automation systems have enabled the development of intelligent roadway management solutions capable of adapting to real-time traffic variations. Adaptive lane management techniques, supported by embedded electronics and connected communication platforms, have emerged as an efficient alternative to costly road expansion projects and complex infrastructure reconstruction. Instead of physically increasing roadway width, these systems intelligently redistribute existing road space according to current vehicular density conditions, thereby maximizing traffic throughput and improving commuter movement efficiency. Within this context, movable traffic separators integrated with automated sensing and control mechanisms offer a practical, scalable, and economically viable solution for implementing dynamic lane allocation in urban transportation networks.
The proposed IoT-enabled Automated Moving Divider for Dynamic Traffic Flow Control system is designed to provide autonomous roadway optimization using real-time traffic monitoring and intelligent divider positioning. The architecture incorporates an ESP32 microcontroller as the central processing unit responsible for traffic analysis, decision-making, and hardware coordination. Dual IR sensor modules continuously monitor vehicular density from both directions of the roadway and transmit real-time input signals to the controller for comparative traffic evaluation. Based on the detected congestion level, the ESP32 activates a DC motor-driven mechanical mechanism that physically repositions the movable divider toward the lower-density lane, thereby allocating additional roadway space to the highly congested side. The system also integrates an LCD module for displaying operational parameters and divider movement status, while an onboard buzzer provides audible alerts during lane transition operations to ensure roadway awareness and operational safety. Furthermore, IoT-based connectivity enables continuous transmission of traffic statistics, divider position information, and system status updates to a centralized remote monitoring platform for supervisory analysis and administrative control. By combining automated sensing, intelligent computation, mechanical actuation, and remote connectivity, the proposed system delivers an efficient and responsive traffic management solution capable of reducing congestion, improving roadway utilization, minimizing travel delays, lowering environmental impact, and supporting the advancement of smart city transportation infrastructure.

2. LITERATURE SURVEY

S. Maiti et al. [1] proposed an IoT-based smart traffic management framework designed to improve urban transportation efficiency through continuous real-time traffic monitoring and intelligent communication technologies. The system utilized connected sensing devices to detect vehicular movement and traffic density across different roadway sections and transmitted the collected information to a centralized traffic monitoring platform. Their work emphasized the importance of adaptive traffic regulation instead of traditional static traffic control approaches. The study demonstrated how sensor-driven automation can improve road utilization, reduce congestion, and support intelligent transportation management. This research strongly supports the real-time traffic density detection and IoT-based reporting architecture implemented in the proposed automated moving divider system. M. A. Razzaque et al. [2] presented a comprehensive survey on IoT middleware architectures and communication frameworks for distributed embedded systems. The study discussed device interoperability, cloud integration, real-time data communication, and efficient information exchange between embedded sensor nodes and remote monitoring platforms. The authors also highlighted the importance of scalability, low-latency communication, and reliable connectivity in IoT-enabled automation applications. Their work provides the technological foundation for the ESP32-based wireless communication and IoT data transmission pipeline used in the proposed dynamic traffic divider framework. V. Varadarajan [3] introduced an automated reversible lane control system for urban roadway networks experiencing uneven directional traffic congestion. The proposed system dynamically reallocates road lanes according to real-time traffic conditions in opposite directions, thereby improving traffic throughput and roadway efficiency. The study highlighted the limitations of fixed lane allocation systems and demonstrated how adaptive lane management can reduce traffic delays and optimize available road space. This work directly validates the movable divider concept and adaptive lane allocation strategy implemented in the proposed automated traffic management system. A. Al-Fuqaha et al. [4] conducted an extensive survey on IoT technologies, communication protocols, enabling architectures, and intelligent application domains. The study examined wireless communication mechanisms, embedded sensing technologies, cloud-based monitoring systems, and distributed IoT infrastructures used in modern automation environments. The authors emphasized the role of IoT in enabling real-time monitoring, remote supervision, and autonomous decision-making in smart infrastructure systems. Their work supports the IoT communication, remote dashboard integration, and centralized monitoring functionalities incorporated into the proposed smart traffic divider framework.

N. H. Barakat et al. [5] developed an embedded traffic density detection system utilizing IR sensors for real-time vehicle identification and congestion analysis. The proposed system used IR sensing modules to continuously detect vehicle presence and monitor roadway traffic density with low computational complexity and rapid response time. Their research demonstrated that IR-based sensing technology is cost-effective, reliable, and highly suitable for embedded traffic management applications. This study directly validates the use of IR_L and IR_R sensors in the proposed system for bidirectional traffic density detection and automated roadway analysis. J. Lee et al. [6] proposed a cyber-physical systems architecture integrating embedded sensing, real-time computation, communication technologies, and automated actuation for intelligent industrial automation environments. Their work established a framework in which physical infrastructure components continuously interact with digital monitoring and control systems through embedded processing and connected communication networks. The study highlighted the importance of autonomous decision-making, real-time sensing, and synchronized actuation for achieving efficient automation. These architectural principles strongly support the integrated sensing, DC motor actuation, and IoT-enabled monitoring mechanisms implemented in the proposed automated moving divider system. R. Prasad et al. [7] reviewed multiple DC motor control techniques used in embedded automation and smart infrastructure applications requiring accurate mechanical actuation and reliable motion control. The study discussed motor-driving circuits, speed regulation mechanisms, torque management, and embedded controller integration for automated physical systems. The authors emphasized that efficient DC motor control plays a vital role in ensuring smooth movement, operational stability, and precise positioning in automated infrastructure environments. Their research demonstrated how embedded motor actuation systems can be effectively utilized for intelligent automation applications involving physical movement and adaptive control. This work directly supports the DC motor-driven divider repositioning mechanism implemented in the proposed automated moving divider system for dynamic lane adjustment and roadway optimization. P. Kumar et al. [8] developed an ESP32-based IoT monitoring platform designed for real-time environmental sensing and wireless communication applications. The proposed framework utilized the ESP32 microcontroller for continuous sensor data acquisition, local embedded processing, and wireless transmission of operational information to connected monitoring platforms. The study highlighted the advantages of the ESP32, including low power consumption, integrated Wi-Fi capability, cost-effectiveness, and high processing efficiency for IoT-enabled embedded systems. The authors demonstrated that the ESP32 can effectively support real-time monitoring, remote accessibility, and intelligent automation tasks in smart infrastructure applications. Their research validates the selection of ESP32 as the primary controller in the proposed traffic divider system for handling sensor data processing, decision-making, and IoT communication.

T. Adiono et al. [9] presented an IoT-based monitoring architecture integrated with embedded sensor nodes and wireless communication technologies for real-time operational analysis and centralized supervision. The system continuously collected sensor information from distributed embedded devices and transmitted the acquired data to a remote monitoring interface through wireless communication networks. The study emphasized the importance of reliable sensor-to-cloud communication, remote accessibility, and efficient data management for modern IoT-enabled automation systems. The authors also demonstrated how IoT-based monitoring platforms can support intelligent decision-making and real-time infrastructure management. Their research strongly supports the IoT dashboard integration, remote traffic supervision, and centralized operational monitoring functionality implemented in the proposed automated moving divider framework. A. Sharma et al. [10] proposed a smart roadway infrastructure system utilizing IoT technologies and embedded sensing devices for adaptive traffic management and congestion reduction. The system continuously monitored vehicular conditions using connected sensors and implemented dynamic traffic control mechanisms to improve roadway utilization and transportation efficiency. The study highlighted the limitations of traditional static traffic management systems and emphasized the importance of intelligent roadway automation capable of responding to real-time traffic variations. The authors demonstrated how IoT-enabled traffic monitoring and adaptive roadway control can significantly reduce congestion and improve vehicle movement in urban transportation environments. Their work closely aligns with the operational objectives, automated traffic balancing strategy, and IoT-enabled architecture of the proposed automated moving divider system. F. Zhu et al. [11] investigated a real-time traffic flow management framework using embedded sensor networks for continuous vehicle monitoring and adaptive roadway control. The proposed system utilized distributed sensing mechanisms to analyze traffic density, vehicular movement patterns, and roadway congestion conditions in real time. Based on the acquired sensor information, the framework implemented automated traffic management responses to optimize roadway efficiency and improve traffic throughput. The study emphasized the importance of rapid sensing, embedded computation, and automated decision-making in intelligent transportation systems. Their research validates the bidirectional traffic density analysis and adaptive control methodology implemented in the proposed IoT-enabled moving divider system for dynamic roadway management. M. Ali et al. [12] developed an automated lane management system integrating IR sensors with microcontroller-based embedded control mechanisms for intelligent traffic regulation. The proposed framework continuously monitored roadway congestion conditions using IR-based vehicle detection modules and dynamically adjusted lane allocation according to traffic density variations. The study demonstrated the effectiveness of combining embedded sensing technologies with automated control systems for improving traffic flow efficiency and reducing roadway congestion. The authors also highlighted the advantages of low-cost embedded traffic monitoring systems in smart transportation applications. Their work directly validates the IR sensor integration, embedded processing architecture, and automated lane management strategy implemented in the proposed IoT-enabled automated moving divider system.

3. PROPOSED SYSTEM

The system architecture is designed as an IoT-enabled intelligent traffic divider control framework built around the ESP32 (Espressif Systems 32-bit Microcontroller), integrating sensing, decision-making, actuation, display, and cloud communication into a continuous real-time loop. During the start or power-on phase, the ESP32 initializes all connected modules, including WiFi (Wireless Fidelity) for network connectivity, LCD (Liquid Crystal Display) for user feedback, servo motor for physical divider movement, buzzer for alert generation, IR (Infrared) sensors for traffic detection, and GPS (Global Positioning System) module for location tracking, ensuring all peripherals are configured and connected properly. Once initialization is complete, the system enters the main loop where it continuously monitors traffic conditions using IR sensors placed on both sides of the road, detecting vehicle presence and determining traffic density or direction. Based on sensor inputs, the system dynamically decides the divider position—left, right, or center—by evaluating logical conditions such as one-sided traffic dominance or balanced flow, and accordingly actuates the servo motor to adjust the divider angle (e.g., 10°, 90°, or 170°), enabling adaptive traffic management. Simultaneously, the LCD updates the current divider status (Left, Right, or Center) to provide real-time visual feedback, while the buzzer generates alerts during position changes to ensure awareness.

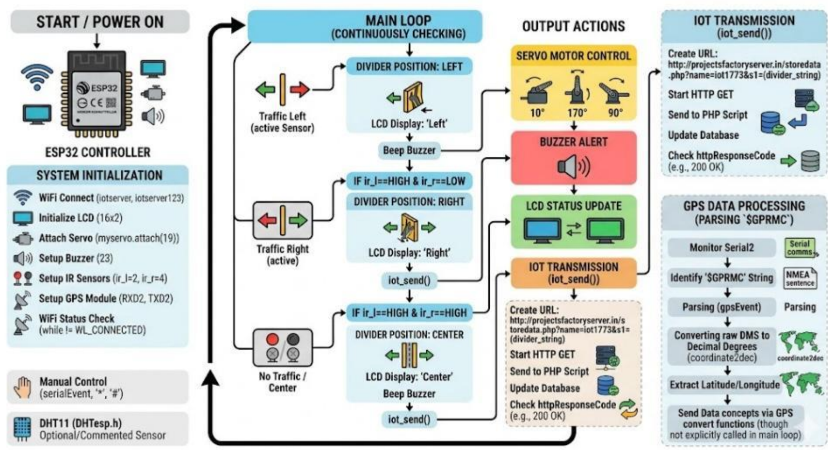

Fig. 1: Proposed system architecture

The system also supports manual override through serial commands, allowing external control when required. In parallel, an IoT transmission module is triggered to send real-time traffic status data to a remote server using HTTP (Hypertext Transfer Protocol) GET requests, where the data is processed by a PHP (Hypertext Preprocessor) script and stored in a database after validating response codes, enabling remote monitoring and analytics. Additionally, the GPS module processes NMEA (National Marine Electronics Association) sentences, particularly the $GPRMC string, to extract latitude and longitude coordinates by converting raw data into decimal degrees, enhancing the system with location-aware capabilities. A continuous synchronization between sensing, processing, actuation, and communication ensures minimal latency and efficient system performance. As illustrated in Fig. 1, this architecture demonstrates a smart, automated, and scalable solution for real-time traffic divider control with integrated IoT-based monitoring and adaptive decision-making

4. RESULT AND DISCUSSION

The Results and Discussion section presents the performance evaluation of the proposed automated barrier gate control system under various operating conditions. The developed prototype, comprising a microcontroller, IR sensors, motor driver, and DC motor-based rack-and-pinion mechanism, was successfully tested for automatic gate operation. Experimental observations indicate that the system accurately detects approaching objects and responds by opening or closing the barrier with minimal delay. The motor control mechanism exhibited smooth and reliable movement, ensuring efficient access control and obstacle management.

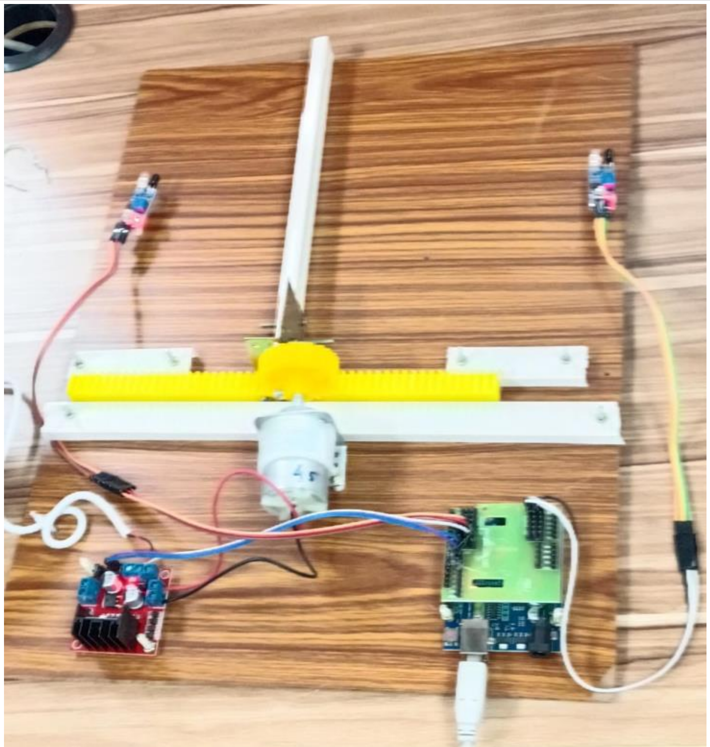

Fig. 2. Experimental prototype of the automated barrier gate control system

Fig. 2 illustrates the developed prototype of the automated barrier gate control system consisting of a microcontroller unit, motor driver module, DC geared motor, rack-and-pinion mechanism, and infrared (IR) sensors. The microcontroller serves as the central controller, processing sensor inputs and generating control signals for gate operation. The IR sensors are employed to detect the presence of vehicles or objects, while the motor driver controls the movement of the DC motor responsible for opening and closing the barrier. The rack-and-pinion mechanism converts the motor's rotational motion into linear movement for efficient gate actuation. Experimental results demonstrate the reliable operation of the system, enabling automatic access control, obstacle detection, and smooth barrier movement in real-time environments.

5. CONCLUSION

The proposed IoT-enabled Automated Moving Divider for Dynamic Traffic Flow Control successfully provides an intelligent and automated solution for adaptive roadway management using embedded sensing and IoT technologies. The system utilizes dual IR sensors for real-time bidirectional traffic density analysis and automatically repositions the movable divider through a DC motor mechanism to optimize lane allocation according to current traffic conditions. The ESP32 controller efficiently manages sensing, traffic computation, motor actuation, LCD status display, buzzer alerts, and wireless IoT communication within a compact embedded platform. Remote monitoring through IoT connectivity enables continuous supervision of traffic conditions and divider operation by traffic management authorities. The system effectively reduces congestion, improves roadway utilization, minimizes travel delays, and supports safer urban transportation management. Furthermore, the modular architecture allows future enhancements such as AI-based traffic prediction, computer vision integration, and large-scale coordinated smart traffic infrastructure deployment for advanced smart city applications.

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