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Modeling and Implementation of a Density-Based Traffic Management System via Programmable Logic Controller

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Traditional traffic signal systems face challenges in efficiently managing traffic when a large number of vehicles move to different lanes. To address this issue, a programmable logic controller (PLC) has been applied Density-Based Smart Traffic Control system using PLC (Programmable logic controller). This work develops a smart traffic control system to keep an eye on the vehicle density at a 4-way junction. Using specific functions, calculations, and logical operations, the system program calculates the traffic density in each lane and transmits data to make automatic decisions regarding traffic signal priorities. The proposed system ensures that the traffic control system adjusts to real-time traffic conditions on the road. By utilizing a PLC (programmable logic controller), all sensors continuously check the position of each lane and perform logical operations. These operations control lanes that require immediate attention and service. Next, the system program is executed to generate output signals to control the traffic lights on the poles, facilitating the switching of red, yellow, or green lights. The duration of the green light, which indicates the ON time for each lane of the intersection, is dynamically adjusted based on the priorities calculated by the system. In summary, the execution of the density-based smart traffic control system with a programmable logic controller enables a more responsive and adaptive approach to traffic management, proficiently allocating priority based on real-time traffic situations at the intersection. This study addresses the challenges of traffic flow with improved safety and reduced congestion at busy junctions.

Keywords: Modelling, Density, Logic Controller, Risk awareness, Traffic management.

Introduction:

Traffic congestion is a significant challenge faced by urban transportation systems across the globe. Conventional traffic light control systems typically operate on fixed timing schedules, regardless of real-time traffic conditions. To address this problem, this study provides a simulation-based design for a density-based traffic system. The main objective of this study was to utilize images to detect traffic quantity. To adjust the durations, there is a need to minimize the waiting time and increase the traffic efficiency. [1]. Urban traffic problems delay and increase fuel costs in cities. The fixed-time-based conventional traffic system is unable to respond early according to the real conditions and manages traffic inefficiently. This study [2] proposed an Arduino-based system to vary the signal time and reduce traffic jams. The optimal and cost-effective solutions are required for efficient management of urban traffic [2]. The study demonstrates that the smart traffic management system utilizes a visual geometrical system to detect the location of traffic congestion using artificial intelligence and machine learning algorithms for real-time traffic detection. This study [3] proposes an innovative approach to detecting vehicle traffic using cameras. An experimental setup using a Raspberry Pi demonstrates the robustness of the model. MATLAB was used to simulate and analyze the behavior of traffic conditions. [3]. The traffic smart management system plays a major role in controlling traffic. Smart management controls emergency vehicles for rescue operations. This study utilized RFID to implement a control system for the passage of automobiles. Based on the vehicle movement, the emergency signal reflects the variation in the signal and automatically controls the process. [4]. Automation-based technologies are increasing globally. Traffic control systems integrated with automation technologies require controllers to automate the system. The communication and network combination between the traffic and road networks is used to control the traffic flow. [5]. Traffic problems are a major challenge worldwide. To overcome this problem, this study provides a prototype to estimate the time and automatically adjust the time to control traffic via real-time decisions. This study provides a computer vision-based traffic estimation methodology using machine learning models.[6]. The increase in population increases traffic congestion, accidents, and violations. Existing traffic management systems often cause delays for emergency vehicles. This study presents the design of a controller implemented using Verilog hardware description language on a field-programmable gate array (FPGA) platform. The controllers are integrated with radio frequency identification (RFID) and infrared sensors to enhance their functionality. They handle counting and timing operations in real-time [7]. Applications in real-time adaptive traffic light control systems reveal designs, implementations, and interventions to alleviate traffic congestion [8]. This study [9] presents how they conducted a literature review related to smart intersections and traffic light control technology. This study outlines the process of identifying relevant articles through searches in academic databases, transportation journals, conference proceedings, and industry reports [9]. The authors in [10] describe a systematic literature review process, involving the identification of relevant studies from academic databases and transportation journals. This study focuses on smart traffic light synchronization, employing an empirical design and incorporating measurable quantitative performance metrics [10]. Another study [11] demonstrates both technological evolution and urban growth based on traffic-light control systems. Innovative traffic light control can be used for traffic density and emergency vehicles [11]. Authors in [12] investigated the relationship between machine learning (ML) applications and traffic light control optimization and demonstrated how machine learning techniques can improve conventional methods for traffic management [12]. The field of data-driven traffic light control has advanced significantly, exploring the opportunities and challenges posed by integrating data analytics with intelligent algorithms to develop more efficient signaling strategies for modern traffic management in the 21st century [13]. The research presented in [14] explores a transportation-focused dynamic traffic light control system. It places particular emphasis on recent advancements and innovative approaches that incorporate IoT-based technologies for managing traffic flow. Additionally, the study compares the effectiveness of IoT solutions with artificial intelligence-based systems for achieving more efficient vehicle control. The study referenced in [12] conducted a systematic review of advanced traffic light control algorithms, emphasizing emerging trends and unbiased techniques in modern traffic management. It examined various algorithms and their roles in enhancing the efficiency, safety, and adaptability of traffic signals in response to evolving patterns of urban mobility. The study cited in [15] presents a systematic review of the literature to identify existing traffic light control strategies and the simulation methodologies used in prior research. It compares the strengths and limitations of these approaches, highlighting gaps in the current body of work that the present research aims to address. The focus on traffic light phasing and pedestrian safety is thoroughly examined through a precisely defined critical review methodology. The inclusion criteria required studies to report on traffic light phasing in connection with pedestrian crossing behavior, injury incidents, and self-reported safety data [16]. Although such conventional traffic light control methods are simple and effective, they suffer from several limitations that can decrease their efficiency or efficacy as a result of traffic conditions [17]. Another study considered cooperative intersection control strategies and concluded that when traffic lights are in equal harmony. This is expected to reduce congestion and minimize overall travel time [1]. The study referenced in [18] offers a comprehensive analysis of the integration of sensor technologies into traffic signal control systems, detailing the types of sensors used, their operational roles, and their impact on vehicle regulation.

Objectives:

The main objective is to reduce congestion on the selected lanes of intersections during peak hours in heavy traffic, and vehicle detection and transfer of data to optimize timings for signals.

Novelty of Work:

This study provides a novel prototype for traffic control integrated with a programmable logic controller, offering an industrial-based control using microcontrollers. Microcontrollers are economical, with less durability and real-time decisions for large industrial setups. The proposed PLC-based system performs faster with the integration of sensors and actuators. The system further dynamically adjusts the signal timings based on the real-time traffic conditions sensed using IR sensors. The IR sensors can accurately detect vehicles and adjust the system automatically.

Material and Methods:

The Mitsubishi PLC Model FX1N was used in this project as the central processor of the control system. FX1N PLCs are compact and reliable solutions for automation tasks. The modular peripheral design provides I/O terminals, such as input/output, that can be selected based on the application address. Therefore, the combination of a robust construction and multifunction programming possibilities designed to absorb the FX1N PLC allowed for the most effective implementation of the project facets. The prototype uses a reflective IR sensor that has an infrared LED emitting infrared light and a phototransistor receiving the reflected infrared light from an object. These sensors are commonly employed to measure distance and detect proximity in various applications.

The entire prototype was formed with a 2 × 2 ft size and placed on a plywood board. A plywood board was used as the base to mount and configure all components. Traffic lights at the intersection. An LED was used to simulate a 4-way pole (but without LEDs). The LED structure was organized following classic traffic light patterns, with red, yellow, and green for every path of directional motion. The further switching of lights for each LED was dynamic based on the input signals acquired from the reflective IR sensors, through which the PLC similarly controlled a reflective traffic signal. Figure 1 illustrates the essential connections between the system's physical components and the corresponding actions, highlighting the network architecture required for effective operation.

In Figure 1, the traffic system continues to function in its usual manner and manages the signal, giving passage to vehicles one after another at each intersection. The system aids in maintaining the orderly flow of traffic and helps prevent congestion at intersections. When no vehicles are detected nearby, it employs a signal skipping strategy, bypassing the inactive signal and advancing to the next one to optimize traffic movement.

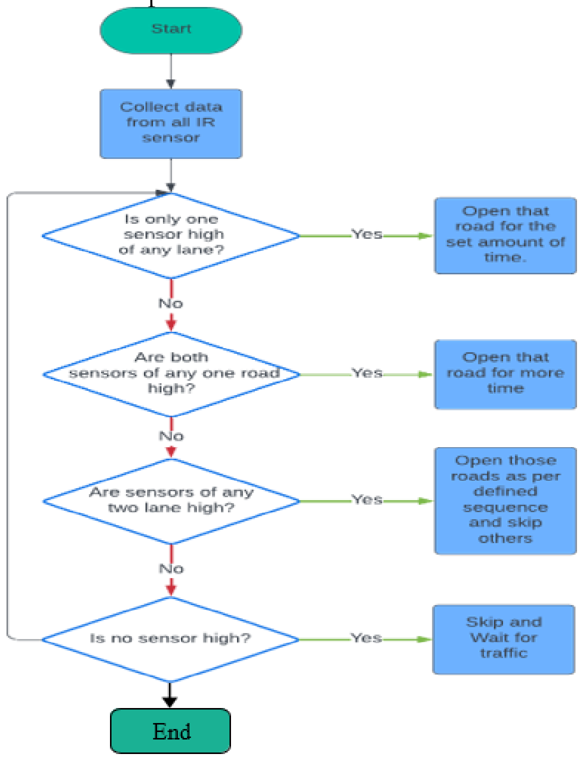

Figure 1. Flow Diagram

Schematic Model:

Figure 2 illustrates the schematic network between the PLC and the sensors.

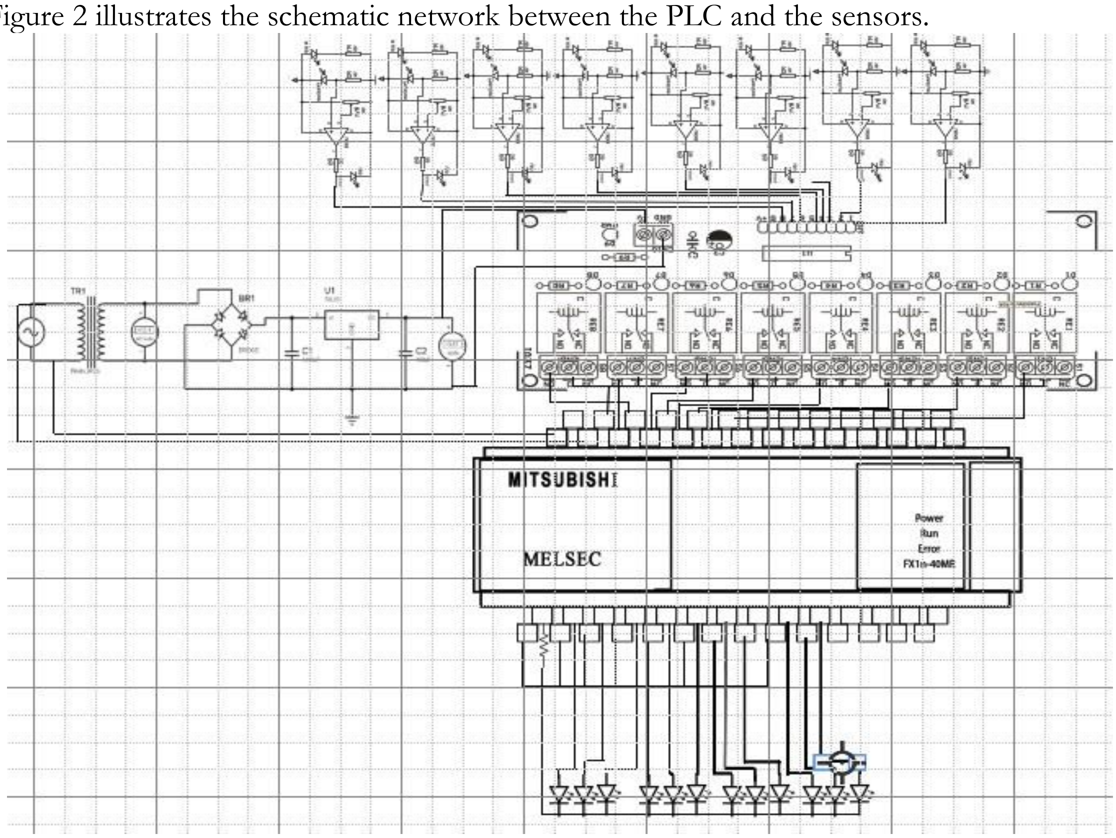

Figure 2. Schematic Model

Components:

Programmable Logic Controller:

The system uses a Mitsubishi PLC panel controller, FX1N, to control the system. A programmable logic control is a type of computer program used in industrial setups, such as manufacturing or other processes. These systems are specifically designed to regulate and oversee procedures and machinery in real time.

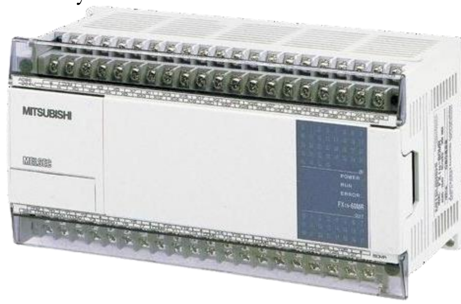

Figure 3. Programmable Logic Controller

Table 1. Programmable Logic Controller parameters

Parameter	Symbol	Unit	Value	Description
Supply Voltage	V_{cc}	Volt	24V	Power Supply Voltage for the Controller
Input Voltage Range	V_{in}	Volt	24V	Voltage range for digital inputs.
Input Current	I_{in}	Milli ampere	7mA per input	Current for each digital input.
Output Voltage	V_{out}	Volt	24V	Output voltage range for digital outputs.

Infrared radiation sensor:

Figure 4. IR sensor

An IR sensor with both a transmitter and receiver are called an IR proximity or reflective sensor. In this system, infrared light is emitted from the transmitter, and the reflected or interrupted light is obtained using a receiver. The presence and proximity of an object can be determined by analyzing whether an infrared signal is detected and evaluating its intensity or range. IR proximity sensors are used in multiple applications, such as object detection, obstacle avoidance, and proximity sensing in electronic devices and automation systems.

Hardware Implementation:

PLCs are chosen as the primary control units for sensor interaction, data processing, and signal timing. The flexibility and programmability of PLCs enable the design and control of logic and algorithms, so that signal timings can be adaptively varied according to real-time traffic conditions. PLCs are responsible for taking input from sensors that detect the arrival of vehicles and calculate the best timing for traffic intersections. The presence of vehicles is detected using infrared (IR) sensors fixed at suitable locations near each signalized junction. IR sensors provide precise and reliable vehicle detection to ensure that the system responds dynamically to changes in traffic volume and congestion levels. PLCs process information received by the IR sensors and allow the system to function in a data-influenced manner to decide when to change which signal. The data collected by the infrared (IR) sensors is processed and managed by programmable logic controllers (PLCs) at each intersection, which in turn control the functioning of their corresponding LED signal heads. LED signal heads provide green, yellow, and red signal phases to control vehicle and pedestrian movements. The adaptive control logic implanted in the PLCs ensures that the signal timings are well optimized to reduce delays or congestion and prioritize safety. Power supply units provide electrical power to PLCs(s), IR sensor(s), LED signal heads, and other electronic components of the system.

Table 2. IR sensor parameters

Parameters	Typical Value/ Range
Operating Voltage	3.3V to 5V
Current Consumption	10mA to 20mA
Output	Type Digital (High/Low) or Analog
Detection	Range 2cm to 30cm
IR LED Wavelength	850nm to 950nm
Response Time	10ms to 100ms

Software Implementation:

The program editor uses Mitsubishi PLC GX Works2 and is compatible with WINDOWS computers. The application comprises the following features/functions: GX Works2 is software used to write, edit, and debug programs for Mitsubishi PLCs. It can support programming using a myriad of languages, including ladder logic, function block diagrams, and structured text; this allows for different types of builds and programming methods. Editing the control logic is a standard option for varying the program. GX Works2 provides various special functions tailored to Mitsubishi PLCs. These may include register editing and settings, file accessing and saving functionalities, contact monitoring, and setting adjustments. The software is user-friendly and has an easy-to-understand, friendly human-machine interface capable of being used by those with no basic ladder logic knowledge and experts. The interface is user-friendly, with intuitive navigation and easy access to all essential features. GX Works2 is a program that has been specifically created with Mitsubishi PLCs in mind, meaning it is tailor-made to be compatible and powerful when used alongside any other Mitsubishi automation products. Supported Communication Protocols and Data Exchange Formats to program or interface Mitsubishi PLCs. The comprehensive set of features and functionalities provided by GX Works2 makes it a versatile tool, serving both as a programming environment and a project management platform for PLC applications. Users can efficiently develop, edit, and manage PLC programs for a wide range of industrial automation applications using this software. The software interface is shown in Figure 5.

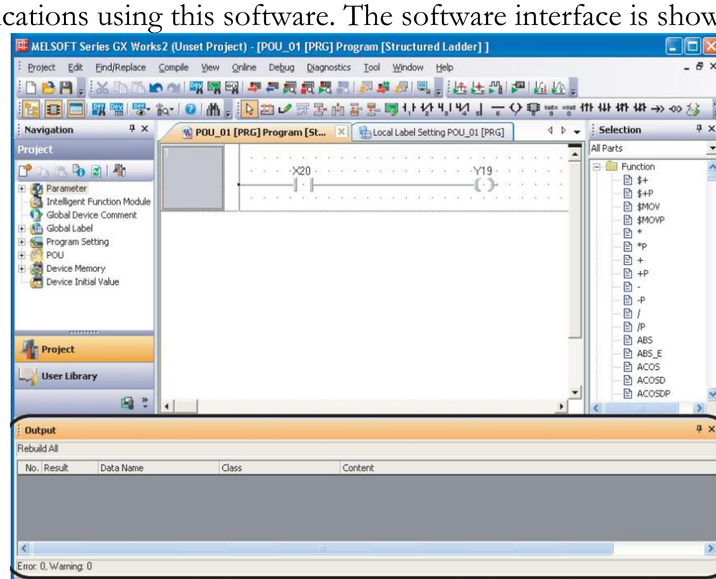

Figure 5. Software interface

Mathematical Model:

Voltage Drop Across Resistor (VR):

$$VR = V_{cc} - V_f \text{ ------ (1)}$$

Resistor Value (R)

$$R = \frac{V}{If} \text{ ------ (2)}$$

IR sensor

Output voltage $$V_{out} = V_{in} \times \frac{R2}{R1+R2} \text{ (3)}$$

Power Consumption Calculation $$P = V \times I \text{ ------ (4)}$$

Required Input Power for Accuracy $$Pin = \frac{Pout}{\eta} \text{ ---------(5)}$$

$$\text{Congestion Reduction} = \frac{Manual\ Congestion - PLC\ Congestion}{Manual\ Congestion} \text{ x 100------ (6)}$$

$$\text{Time saved} = \frac{Manual\ Time - PLC\ Time}{Manual\ Time} \text{ x 100------ (7)}$$

Cycle Time=Time taken for sensing + logic execution + output switching ------ (8)

Table 3. Metrics Results

Output Voltage	Power Consumption	Accuracy	Congestion Reduction	Time Saved	Response Latency
12	0.168	50%	45%	37%	10 ms

The results indicate that the is accurate and performs actual saving, congestion rejection, and response latency over the manual system.

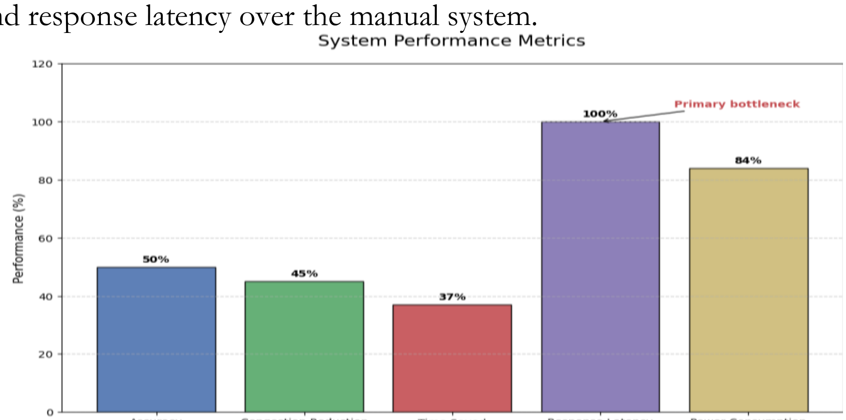

Figure 6. Performance Metrics Comparison

Results and Discussion:

In the outcome phase, the layout and implementation on a plywood board provided a useful testing platform for the software development of an active traffic control system that can monitor vehicles independently in real time and control them based on the detected density. The application of a smart traffic light control system through PLCs and IR sensors provides a solution with several advantages to improve traffic flow efficiency and eliminate congestion, as well as car accidents that take place on the road.

Prototype Testing: During the testing phase, the system assesses the efficiency and operation of the designed system. The test cases are shown in table 4,5 and 6.

Table 4. Prototype Testing Case 1

Preconditions	**The traffic control system is powered on and connected to the PLC**
Actions	Activate the PLC and sensors.
Expected Result	System Start

Result	Pass

Table 5. Prototype Testing Case 2

Preconditions	The controller and sensors are loaded
Actions	Activate the PLC and sensors at a well-lit scene with traffic congestion.
Expected Result	The IR sensors detect and manage the traffic signal lights.
Result	Pass

Table 6: Prototype Testing Case 3

Preconditions	The traffic detection system is running
Actions	Move a detectable object into the IR sensor region.
Expected Result	The system provides accurate and timely detection of objects.
Result	Pass

Optimized Traffic Flow:

Improved Road Safety:

Smart System: These smart traffic light control systems, using PLC and IR sensors, maintain signal timings according to the real-time traffic data, thus resulting in better management of flow and reduced delay and congestion at intersections. The system utilizes IR-based sensors installed at all intersections to monitor and analyze dynamic data continuously in real time, and subsequent modifications are then carried out to optimize traffic flow and alleviate congestion. The processes keep pedestrian crossings, emergency vehicles, and other safety features in mind, resulting in fewer accidents overall, making the entire road safer. Although the costs of smart systems, such as PLCs via IR sensors and advanced control algorithms, may result in higher initial costs, these capital expenses continue to represent recovery potential by increasing traffic flow efficiency, which subsequently reduces spending on fuel consumption and maintenance. In addition, smart systems help preserve the environment by maximizing traffic flow, reducing idling time, and easing smooth vehicle movements, which reduces emissions and promotes clean air.

User Interface: In the designed smart traffic control system, the IR sensors are turned to active mode and start sensing vehicles at all intersections. Every IR sensor is connected to a relay module, and this relay acts as a switch that passes the status of either high or low from the sensor to the PLC. The IR sensors detect the overhead movements of vehicles or their proximity. When a vehicle is detected, the sensor sends a high signal to the relay module. In the absence of a vehicle, the sensor provided a low signal. The relay module sends the status information (high/low) of each IR sensor to the PLC. The PLC can use this information to ascertain the traffic situation at a particular intersection. The signal timings at the intersections vary depending on the traffic conditions determined by the IR sensors, which are controlled by the PLC.

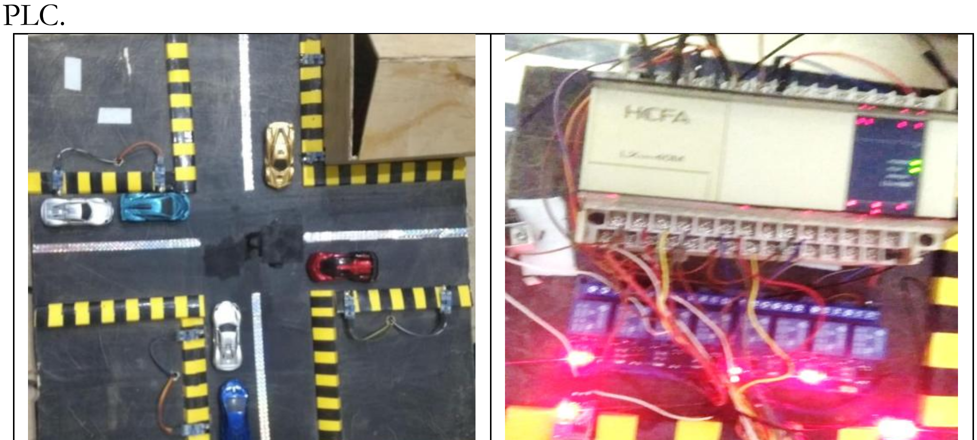

Figure 7. Hardware Setup

Conclusion:

In Traffic management, we can successfully implement a traffic light system using a PLC. An advanced traffic signal was proposed and implemented by incorporating intelligent sensors with a PLC module. With this integration, the complete traffic system is synchronized effectively, and enormous time delays can be avoided when controlling and managing traffic. Sensors can be used to interface with the PLC module, which would enable the system to detect whether a vehicle is present and change the signal timings accordingly. This dynamic response capability not only reduces road congestion but also ensures that vehicles can move smoothly at junctions and decreases the number of accidents that occur. Finally, as an incremental improvement, a larger number of sensors enhanced the overall design of the traffic light system. With supplementary sensors installed around roads at key positions, more complete and extensive coverage can be achieved for unprecedented traffic management and improvement.

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