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Smart Traffic Light Management System: A Novel Approach Using IoT and AI for Emergency Handling and Congestion Reduction

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Abstract. City traffic congestion, together with ineffective traffic signals, continues to pose significant problems in metropolitan areas, which results in longer travel times and worsened pollution while also delaying emergency responses. This paper proposed a smart traffic light control system that implemented IoT alongside RFID and real-time camera detection of objects for enhancing emergency vehicle prioritization and managing traffic flow. The system continuously adapts traffic light intervals according to existing traffic amounts, which results in fewer jams and decreased waiting periods for all vehicles. Emergency vehicle detection through RFID technology directs ambulance and fire truck vehicles to safely access intersections without delays. The system utilized Arduino microcontrollers alongside ESP32-CAM modules and Python-based object detection algorithms for implementing the system that proved its success in handling complex traffic situations. The implemented system generated important results, which improved traffic efficiency while lowering vehicle emissions and accelerating emergency response service. AI, alongside IoT technologies, enables the system to bring transformative changes to how cities manage their urban traffic flow by delivering both expandable and eco-friendly solutions for smart cities. Intelligent traffic systems demonstrate essential value for tackling modern urbanization-related challenges as well as pollution problems and public safety issues.

Keywords: traffic Light Control System, IoT, RFID, Emergency vehicle, ESP32-CAM and AI

1. Introduction

During the previous two hundred years the worldwide human count has expanded substantially beyond 8.2 billion people in 2024 [1]. Industrialization has resulted in rapid population growth that created an excessive rise in vehicle use particularly in expanding cities unable to manage growing transportation requirements [2]. The rapid rise in global population has turned traffic congestion into a primary problem which leads to delayed journeys and increased fuel use and higher emissions of pollutants [3].

Current traffic management systems including fixed-time traffic lights show no capability of responding to present-day traffic conditions, the mechanisms are non-adaptable leading to two types of operational inefficiencies which cause both free-flowing roads to wait needlessly and heavily burdened routes to remain jammed [4]. These systems neglect to give emergency vehicles priority status which results in serious delay situations that potentially lead to fatal injuries together with significant property destruction. The economic impact of inefficient traffic control consists of wasted travel time and increased fuel usage and declining public health related to extended periods of breath of vehicle emissions [5].

This paper proposes a Smart Traffic Light Management System based on AI and IoT integration technology to achieve traffic optimization. The system makes dynamic changes to traffic signal durations based on current data while using RFID to put emergency response units at the front of queues. The system's integration of ESP32-CAM detection modules with Arduino microcontrollers leads to improved efficiency together with reduced congestion while enabling future growth of urban areas. The rest of the paper is structured as follows: Section 2 presents the related work. Section 3 describes the System design and method used. Section 4 shows the Implementation of the proposed model. Section 5 shows the results and discusses the findings. Section 6 concludes the paper.

2. Related works

Nwobodo [6] proposed intelligent traffic control systems that rely on CCTV images for gathering and monitoring traffic, current systems may not work effectively under certain conditions, such as poor weather or in rural areas with limited infrastructure.

Shrestha et al. [7] created a video processing system based on traffic lights as a congestion reduction method. Real-time traffic images are captured through video cameras before utilizing image subtraction together with binary image techniques for processing. The Raspberry Pi receives processed data from the system for managing traffic light operations. This improved flow of traffic lacks emergency vehicle detection which limits its effectiveness in sudden critical situations.

Purnamasari and Nurwildani [8] proposed a novel graph-based algorithm that integrates spatiotemporal graph convolutional networks (ST-GCN) with reinforcement learning techniques, The algorithm dynamically adjusts traffic signals, reroutes vehicles, and provides real-time guidance based on sensor and environmental data. The proposed algorithm is primarily tested in a simulated urban environment rather than real-world settings. This limits its ability to account for unpredictable real-world variables, such as sudden weather changes or human driver behavior [8].

Hazarika et al. [9] proposed a vision-based DTLS using the YOLO (You Only Look Once) object detection algorithm that detects and counts the total number of vehicles on the roads of a traffic signal junction, the traffic signals are tuned based on the computed traffic to minimize the overall delay at that junction.

Kumar et al. [10] proposed an automated intelligent traffic monitoring and controlling system using YOLO V3 neural architecture and implemented to detect the emergency vehicles from video stream data from UAVs using deep Convolution Neural Network (CNN) along with

rerouting algorithm to provide the safest alternate route from current position to destination, in a heavy traffic environment.

The reviewed studies highlight the potential of IoT, AI, and RFID technologies in improving traffic management. However, existing systems often focus on specific aspects of traffic management, such as congestion reduction or emergency vehicle prioritization, without providing a comprehensive solution. This paper addresses this gap by proposing a Smart Traffic Light Management System that integrates real-time traffic detection, emergency vehicle prioritization, and adaptive traffic light control.

3. System design and method

The proposed smart traffic light control system consists of the following physical components:

1. Arduino Uno R3: A microcontroller board that controls the traffic light signals based on input from cameras and RFID readers.

2. ESP32-CAM: A Wi-Fi-enabled camera module that captures real-time traffic images and streams them to the system for object detection.

3. RFID-MRC522: A module that detects emergency vehicles equipped with RFID tags, allowing the system to prioritize their passage.

4. LEDs: Simulate traffic lights in the system.

5. Jumper Wires and USB Cables: Used for connecting the physical components.

The following tables (Table **1** and **2**) demonstrates the physical and software components and their tasks in the proposed system:

Table 1. Demonstrates the physical components and their task.

Components	Task
Arduino Uno Board [11]	Microcontroller board receives the code from IDE to control other physical devices.
RFID RC-522 Reader [12]	Is a form of wireless communication that incorporates the use of electromagnetic or electrostatic coupling in the radio frequency portion of the electromagnetic spectrum to Uniquely identify an object.
Jumper Wires [13]	Jumper wires are used for making connections between items on your breadboard and your Arduino's header pins.
RFID Embedded Code Card & Tag [14]	Both contains Unique code which are detected and processed by RFID-MRC522 Module.
Esp32-Cam [15]	ESP32-CAM is a WIFI+ Bluetooth dual- mode development board that uses PCB on-board antennas and cores based onESP32 chips.
USB 2.0 Cable Type A/B [16]	Used to upload the code from IDE to Arduino Board.
LEDs (Light Emitting Diodes) [17]	Acts as a sign of the brightness.

Data cable USB 2.0 micro-USB [18]	Used to connect Esp32-Cam to power supply.

Table 2. Demonstrates the Software Components and their task.

Components	Task
Arduino IDE [19]	Arduino IDE is an open-source software that is mainly used for writing and compiling the code into the Arduino Module.
PyCharm IDE [20]	PyCharm is an integrated development environment (IDE) used for programming in Python. It provides code analysis, a graphical debugger, an integrated unit tester, integration with version control systems, and supports web development with Django. PyCharm is developed by the Czech company JetBrains.
Fritzing [21]	Is a software that used to design the circuits.

3.1 Circuit Design:

The circuit design process means how to make the physical connection between the required components (Arduino and other suitable components) to design a smart traffic light system by jumper wires and USB cables as needed. the circuit design made by the Fritzing IDE. The below figure demonstrates the physical connection between system components:

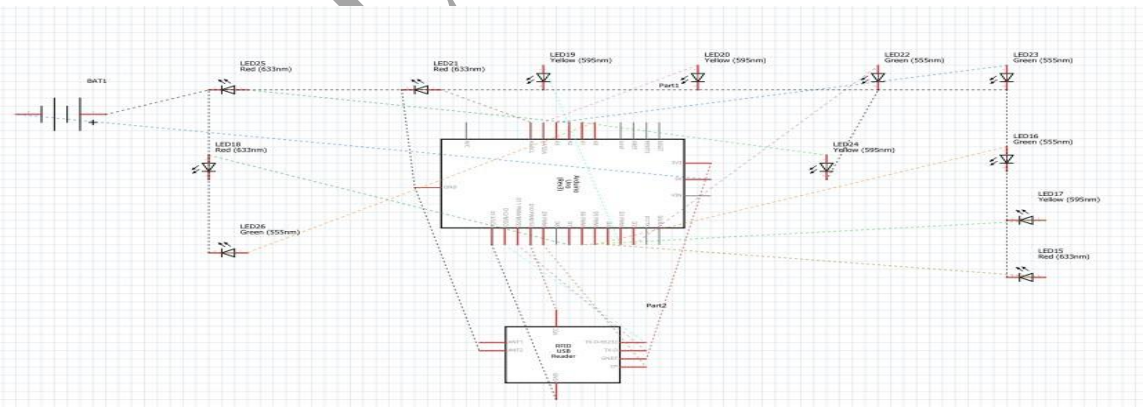

Figure 1. Demonstrates the System Circuit Design.

The following table demonstrates physical connection between Arduino and RFID Reader.

Table 3. Demonstrates physical connection between Arduino and RFID Reader.

Signal	MFRC522 Reader/PCD Pin	Arduino Uno /101 Pin
RST/Reset	RST	9

SPI SS	SDA(SS)	10
SPI MOSI	MOSI	11 / ICSP-4
SPI MISO	MISO	12 / ICSP-1
SPI SCK	SCK	13 / ICSP-3
+	GND	GND
-	3.3V	3.3V

3.2 System operations:

The system operates as follows:

- Real-time images from ESP32-CAM modules send data to the system through which OpenCV in Python performs object detection.
- The RFID readers inside the road identify emergency vehicles as they possess RFID tags. The system changes traffic light signals according to the priority status of vehicles it detects.
- The Arduino microcontroller uses camera and RFID reader data to provide real-time signal adaptation for traffic lights through its processing functions for congestion reduction and traffic optimization.

4. Implementation:

This section demonstrates the implementation of a smart traffic light control system and describes the way that the system works and how this system receives information from different cameras that are distributed across the intersection in order to treat normal vehicle traffic and how the system treats emergency cases by receiving data from RFID that is installed in the road section; the following figures demonstrate this by more details:

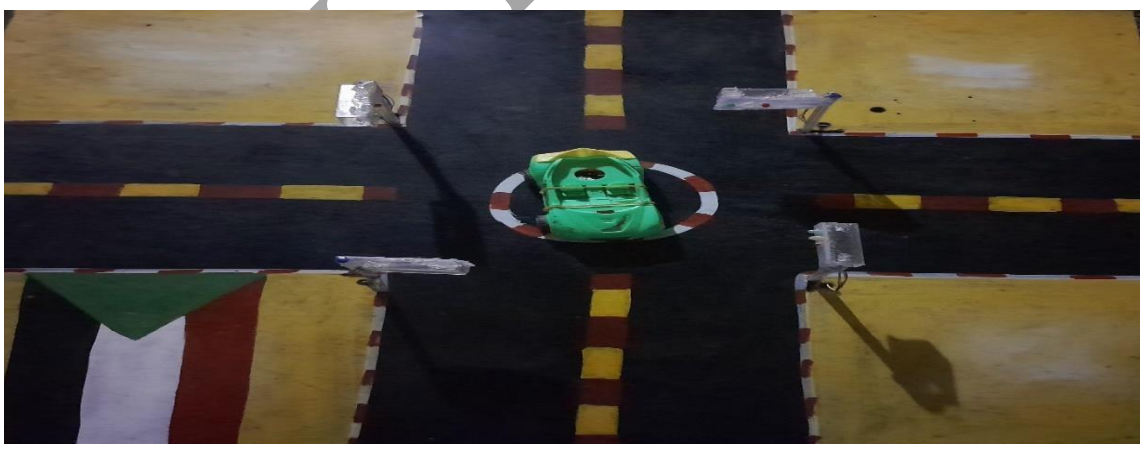

Figure 2. Demonstrates the whole intersection.

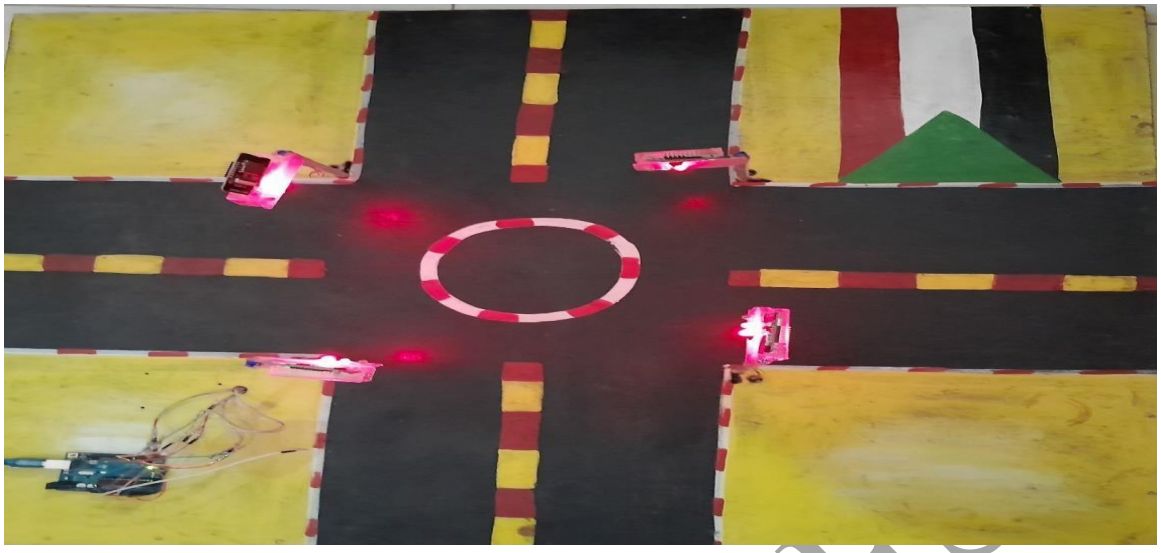

Figure 3. Demonstrates the empty intersection.

4.1 Normal Traffic Management:

In the absence of emergency vehicles, the system uses the camera feeds to detect the number of vehicles on each road and adjusts the traffic light signals accordingly. Roads with higher traffic density are given priority, reducing waiting times and congestion.

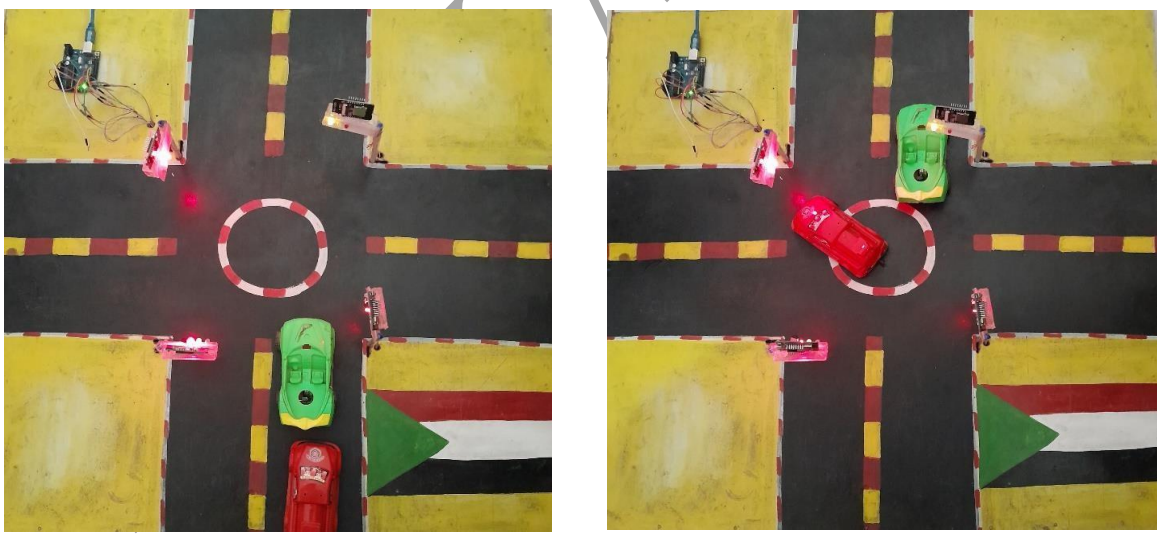

Figure 4. demonstrates the normal vehicles passing.

4.2 Emergency Case Handling:

When an emergency vehicle is detected by the RFID reader, the system immediately prioritizes its passage by turning the corresponding traffic light green and halting traffic on other roads. This ensures that emergency vehicles can pass through the intersection safely and quickly.

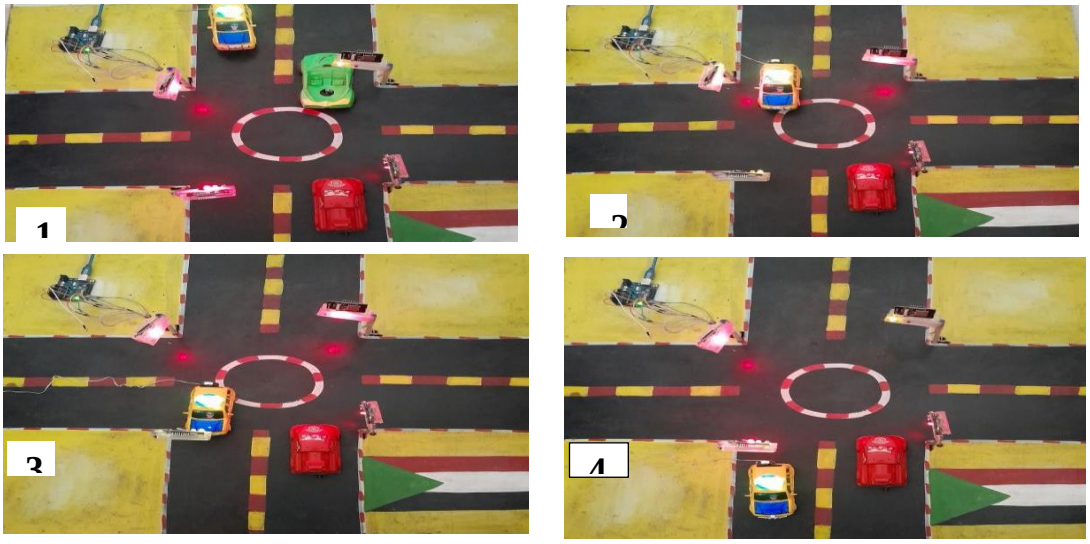

Figure 5. Demonstrates passage of emergency vehicles after getting instruction from system when the data received from RFID.

4.3 Implementation Code:

This project consists of two main execution programs, each developed in a different language. The first one has been written in Python language using the PyCharm IDE to use OpenCV libraries for object detection. The main aim of the first program is to send a command to the Arduino IDE via the serial library as 1, 2, 3, or 4, representing cam1, cam2, cam3, and cam4, respectively, when one or all cameras detect a car, as shown in the below figure:

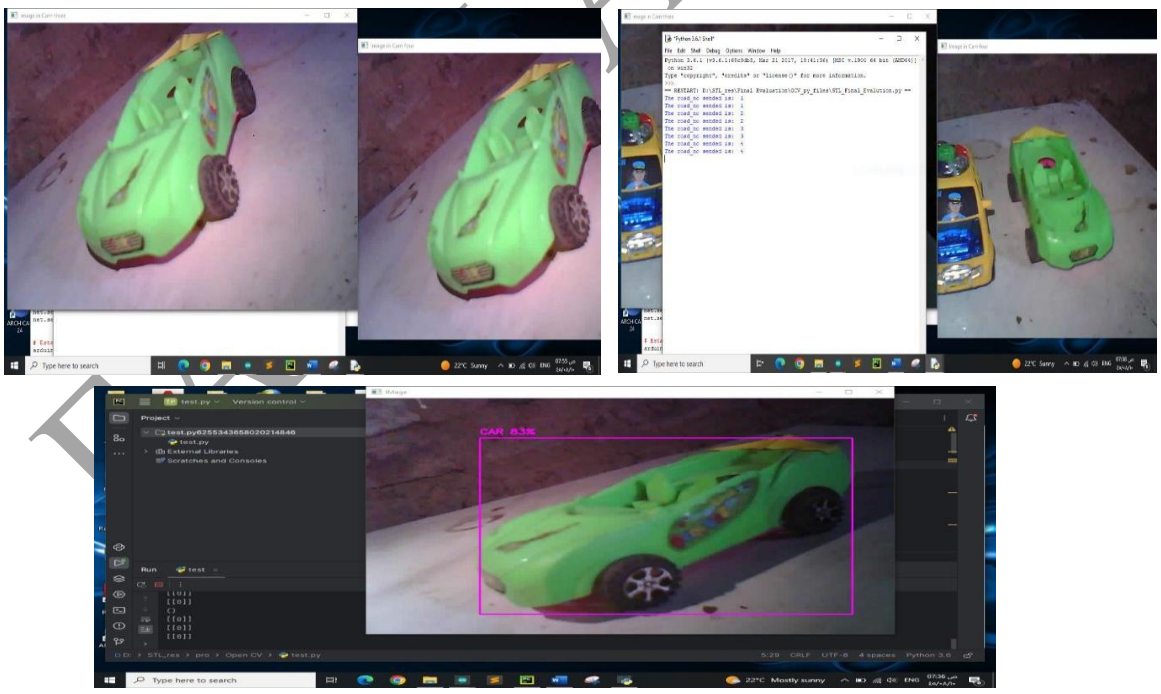

Figure 6. Demonstrates python program implementation using ESP32 cam.

The other program was written in Arduino language (C language + special libraries) for physical instruction in Arduino using Arduino IDE to write and upload the code into

Arduino.

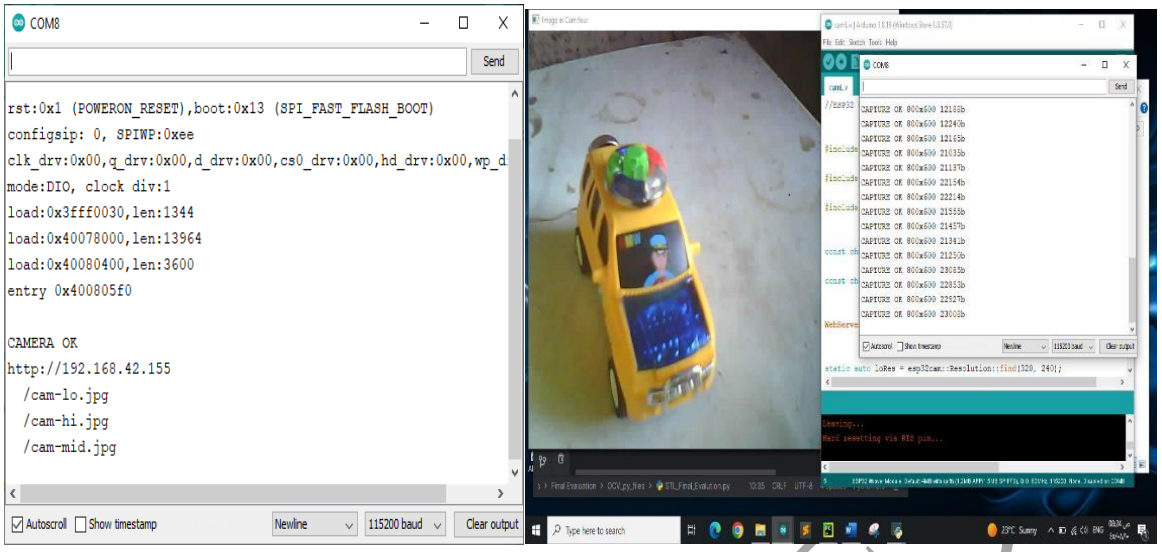

Figure 7. demonstrates Arduino Ide serial monitor.

5. Results and Discussion

Multiple implementation indicators demonstrate the Smart Traffic Light Control System effectively addresses critical issues in urban traffic control. The IoT (Internet of Things) and RFID (Radio-Frequency Identification) and real-time camera-based object detection technologies in the system enable optimal traffic flow and congestion reduction with emergency vehicle priority protocols. The designed system effectively implements its real-time operational capabilities for dynamic traffic adaptation to present traffic conditions and minimizes waiting times and improves roadway security features. RFID technology ensures emergency vehicles gain time-efficient and protected route access at intersections thus improving safety during critical times. Environmental sustainability at an urban level receives support from this system which demonstrates its pollution reduction capabilities by reducing traffic congestion.

6. Conclusion

This study demonstrates the substantial changes that occur when cities use smart traffic light control systems in their operation. A combination of multifunctional cameras with priority processing and RFID tools with emergency response adaptability systems creates major urban improvements through traffic improvement and pollution reduction and increased security and better urban living conditions. Smart traffic management systems prove essential for smart cities by demonstrating their ability to solve intricate traffic challenges and maintain sustainable efficient urban transportation systems. The investigation done here provides foundations for future work which evaluates progressive machine learning algorithm applications for forecasting traffic patterns under changing conditions, to enable smooth integration with connected cars and guarantee the system's safe functioning, it is imperative to give priority to better communication protocols and strengthened cybersecurity measures.

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