

# An IoT-Enabled Smart Zebra Crossing System With PIR Sensors And IP Camera-Based Pedestrian Counting For Road Safety

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## **Abstract**

Due to more cars on the road and pedestrians acting in strange ways, pedestrian safety at zebra crossings is a big problem in cities. This paper presents an intelligent automated zebra crossing system that utilises Passive Infrared (PIR) sensors, Internet of Things (IoT) technologies, and IP camera-based pedestrian counting methods. PIR sensors can tell right away whether there are people walking by, but the IP camera uses computer vision techniques to accurately measure how many people are walking by. This dynamic analysis lets the system change the timing of signals in a way that increases the amount of time people spend crossing. Edge computing is used to make processing with low latency easier and make sure that the system works reliably without always needing the cloud. The IoT architecture makes it possible for system parts to talk to each other, watch each other, and control each other in real time. Experimental results demonstrate that the proposed method significantly promotes pedestrian safety, reduces waiting times, and improves traffic flow efficiency compared to conventional fixed-time systems, establishing it as a feasible option for smart city and intelligent transportation projects.

**Keywords:** Smart Zebra Crossing, Pedestrian Safety, PIR Sensors, Internet of Things (IoT), Computer Vision-Based Pedestrian Counting

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## **I. Introduction**

As cities grow quickly and more cars are on the road, traffic jams and accidents involving pedestrians have become major problems. Zebra crossings are meant to keep pedestrians safe, but they don't always work as well as they could since they don't have adaptive control systems. Most traditional systems use fixed-time signal strategies that don't take into account changes in pedestrian demand or traffic flow in real time. This makes people wait longer, makes crossing the street less safe, and wastes road space (Singh & Kaur, 2022; Zhang et al., 2025). Traffic jams not only pose safety problems, but they also have a big economic cost since they lower productivity, lengthen travel times, and use more fuel. This shows how important it is to find smart ways to manage traffic.

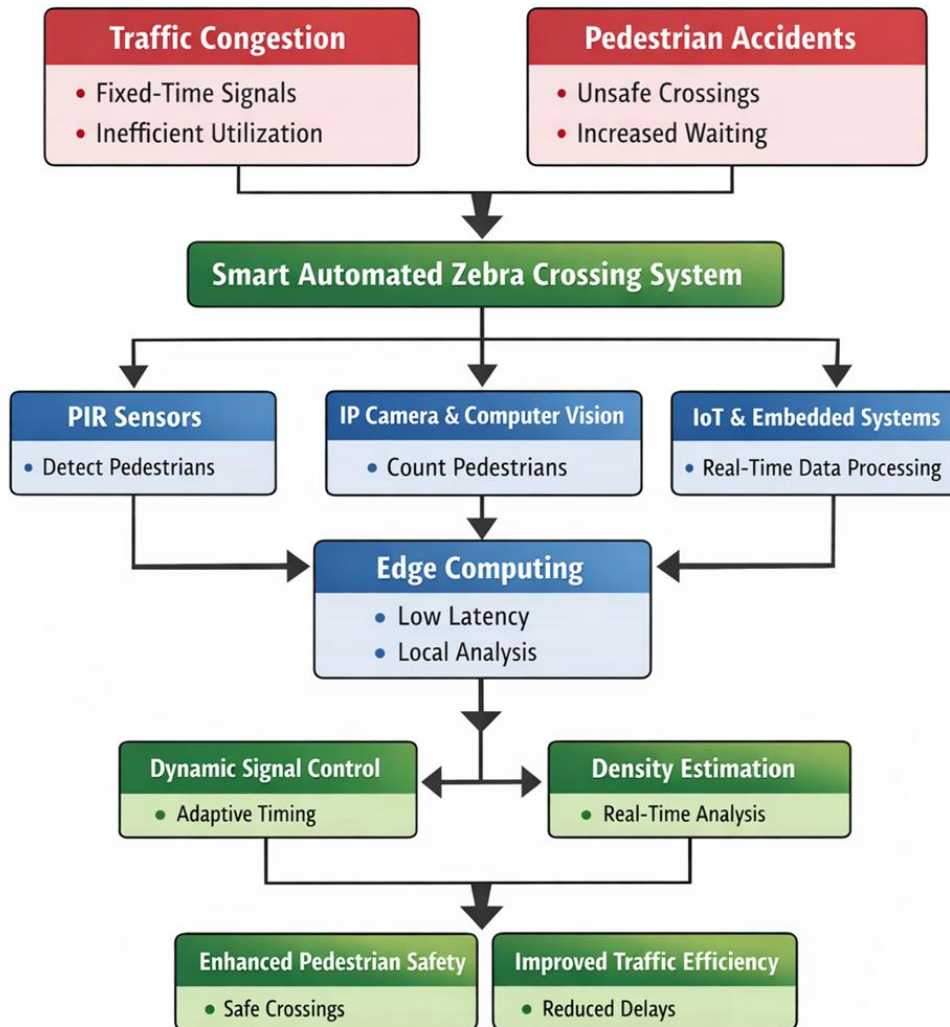
Recent improvements in computer vision, embedded systems, and the Internet of Things (IoT) have made it possible to create adaptive and data-driven traffic control systems. IoT-based frameworks allow sensors, controllers, and monitoring platforms to talk to each other without any problems, which makes it possible to collect and make decisions based on data in real time (Santos et al., 2023). Computer vision methods have also made it much easier to find pedestrians and figure out how many people are in a certain area, even when the weather is bad or the city is busy (Chen et al., 2024; Kandavel et al., 2025). Combining data from several sensors, like vision systems and motion sensors, makes the system more reliable and robust (Dhuvey et al., 2024).

In this regard, the current study offers an intelligent automated zebra crossing system that integrates Passive Infrared (PIR) sensors with IP camera-based pedestrian counts inside an Internet of Things (IoT)-enabled framework. The PIR sensors can tell if a person is there in real time, and the camera module uses computer vision techniques to get an accurate estimate of how many people are in the area. To make sure low latency and dependable operation without relying too much on cloud infrastructure, this information is processed utilising edge computing methods. The system changes the timing of signals in real time based on the data it has analysed. This optimises the length of time it takes for pedestrians to cross based on how many people are really crossing.

The suggested method not only makes crossing safer for pedestrians by decreasing dangerous situations, but it also makes traffic flow better by cutting down on unnecessary delays. The system is a scalable and cost-effective solution that can be used in smart city environments and next-generation intelligent transportation systems. It uses the latest technology and smart control strategies to do this.

An automated zebra crossing system that is both clever and efficient is shown in Figure 1. The first step is to use PIR sensors to identify pedestrians in real-time, and then to estimate the density of pedestrians using an

IP camera and computer vision methods. Low latency and dependable operation are achieved by transmitting the collected data via an IoT-enabled framework and processing it at the edge. The system uses this data to optimise the amount of time pedestrians spend crossing the street by adjusting the timing of the signals on the fly. Improved traffic efficiency through reduced delays and adaptation to real-time situations is achieved through an integrated process that promotes pedestrian safety.



**Fig. 1** Workflow Diagram of the Proposed Smart Automated Zebra Crossing System for Adaptive Pedestrian Safety and Traffic Management

## II. Related Work

Recent studies in intelligent transportation systems have concentrated on enhancing pedestrian safety at zebra crossings via sensor integration, IoT frameworks, and computer vision methodologies. In the past, basic sensing technologies like infrared and ultrasonic sensors were mostly used to find pedestrians and set off crossing signals. For example, Sivamani et al. (2025) created a smart pedestrian safety system that used PIR and ultrasonic sensors to make crosswalks safer and easier to see. The system worked in a way that saved energy and responded in real time. Othman et al. (2022) have suggested an IoT-based pedestrian crossing system that uses PIR sensors and alarm systems to help both walkers and automobiles, especially on campus.

There have also been studies on wireless and embedded solutions to make infrastructure less complicated. Hashim (2020) developed a portable smart pedestrian crossing system that utilises PIR sensors and wireless connection, enabling cost-effective and dependable pedestrian detection and automatic signal management. Lakshmi et al. (2025) also introduced an IoT-based pedestrian zone safety system that uses sensors and camera-based AI models to control pedestrian paths and keep cars from getting in where they shouldn't.

Recent research underscores the significance of multi-sensor data fusion and real-time analytics, propelled by advancements in IoT and artificial intelligence. Zhang et al. (2025) created an IoT-enabled system for detecting pedestrians that used multi-sensor fusion and improved deep learning techniques. It was able to accurately recognise pedestrians even when there were a lot of them. Also, IoT-based traffic monitoring systems that use deep learning have shown that they can work better and grow in real-time traffic situations (Kumar et al., 2023).

Computer vision-based methods have gotten a lot of attention since they can accurately find pedestrians and figure out how many there are. High-accuracy, low-latency real-time pedestrian recognition is possible with advanced models like YOLO-based detection frameworks (Kandavel et al., 2025). Efficient deep learning architectures like YOLOped improve performance even more in contexts with limited resources, making them perfect for smart camera systems that run on the edge (Kyrkou, 2020). Multimodal detection strategies that combine optical and thermal data have also been suggested to make detection more accurate in difficult situations, as when there isn't much light (Dasgupta et al., 2021).

A number of studies also stress how important sensor fusion and smart decision-making are for smart crosswalk systems. Ullatil (2020) examined diverse pedestrian sensing technologies and their roles in enhancing safety at crossings, highlighting the necessity for integrated systems that amalgamate numerous sensing modalities. Also, new AI-based frameworks combine deep learning, natural language processing, and contextual analysis to make traffic control more flexible and make it easier to get around in cities (Kandavel et al., 2025).

Even with these improvements, current systems still have problems including needing a lot of processing power, latency concerns because they rely on the cloud, and less accuracy in complicated urban situations. Additionally, many solutions only function with either sensor-based detection or vision-based analysis. They don't have a single framework that includes real-time detection, density estimation, and adaptive signal regulation.

To fill these deficiencies, the proposed approach combines PIR sensors with IP cameras to count pedestrians in an IoT-enabled architecture that uses edge computing for fast processing. This hybrid method uses the best parts of both sensing and vision-based methods to make intelligent zebra crossing systems in smart cities more reliable, flexible, and scalable.

### **III. Proposed Solution**

The proposed smart automated zebra crossing system is designed as a comprehensive and intelligent framework that seamlessly integrates sensing, processing, and communication technologies to address the limitations of conventional pedestrian crossing systems. By leveraging real-time data acquisition and adaptive control strategies, the system ensures enhanced pedestrian safety while simultaneously improving overall traffic efficiency.

At the sensing layer, the system employs Passive Infrared (PIR) sensors strategically positioned near the zebra crossing to enable automatic pedestrian detection. These sensors continuously monitor infrared radiation changes caused by human movement and instantly identify the presence of pedestrians approaching or waiting to cross. This mechanism ensures immediate system activation without requiring manual input, thereby reducing human dependency and enhancing responsiveness. The use of PIR sensors also contributes to low power consumption and cost-effective deployment, making the system suitable for large-scale urban implementation.

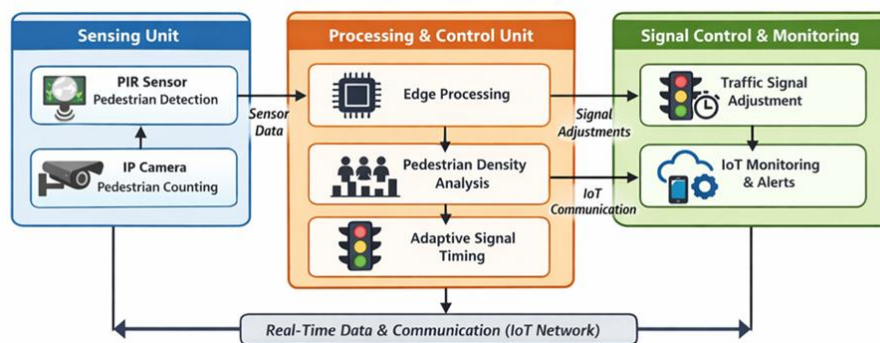
To complement the basic detection capability, the system incorporates an IP camera for real-time pedestrian headcount and density estimation. The camera captures continuous video streams of the crossing area, which are processed using advanced computer vision algorithms. These algorithms perform tasks such as object detection, tracking, and counting to accurately determine the number of pedestrians and their movement patterns. This enables the system to distinguish between isolated pedestrians and crowd scenarios, providing a more granular understanding of real-time conditions. Additionally, the vision-based approach enhances system reliability under diverse environmental conditions, including varying lighting and complex backgrounds.

The processing layer of the system is implemented using edge computing techniques, where data from sensors and cameras is analyzed locally at the device level. This reduces latency significantly compared to cloud-based processing and ensures faster decision-making, which is critical for real-time traffic control applications. Edge processing also enhances system reliability by minimizing dependency on continuous internet connectivity and reduces bandwidth requirements for data transmission.

Based on the processed inputs, the system implements adaptive signal timing, which forms the core functionality of the proposed solution. Unlike traditional fixed-time traffic signals, the system dynamically adjusts the pedestrian crossing duration according to real-time pedestrian density and traffic conditions. For instance, during peak hours with high pedestrian volume, the system allocates longer crossing times to ensure safe passage, whereas during low-demand periods, the signal duration is reduced to maintain smooth vehicular flow. This intelligent adaptation minimizes unnecessary waiting times for both pedestrians and vehicles, thereby improving user satisfaction and road utilization efficiency.

Furthermore, the system is integrated with an IoT-based communication framework that enables real-time monitoring, control, and data exchange between various components, including sensors, processing units, and central management systems. This connectivity allows authorities to remotely monitor system performance, collect historical data for analysis, and implement updates or control strategies as needed. The IoT integration also facilitates scalability, enabling the deployment of multiple interconnected smart crossings across urban areas as part of a unified smart city infrastructure.

In addition to its core functionalities, the proposed system offers significant advantages such as reduced accident risk, improved compliance with pedestrian signals, and optimized traffic flow. The hybrid integration of PIR sensors and camera-based analytics ensures high accuracy and robustness, while edge computing guarantees timely and reliable operation. Overall, the system provides a scalable, efficient, and intelligent solution for next-generation pedestrian safety and traffic management, aligning with the objectives of smart city development and sustainable urban mobility.



**Fig. 2** Block Diagram of the Proposed IoT-Enabled Smart Automated Zebra Crossing System

Figure 2 shows the block diagram of the suggested smart automated zebra crossing system that works with the Internet of Things (IoT). It shows how the sensing unit, processing and control unit, and signal control and monitoring module all work together. The PIR sensors and IP camera gather real-time data on pedestrians. This data is then processed using edge computing methods to figure out how many people there are and make decisions. Based on this study, adaptive signal timing is used to control pedestrian crossings. The IoT framework makes it possible to communicate, monitor, and control all the time, which makes the system perform better and makes pedestrians safer.

#### IV. Result Analysis

To fully compare the proposed smart automated zebra crossing system with a traditional fixed-time control system, we looked at key performance indicators such as pedestrian wait time, accident risk, traffic delay, and system reaction time. These measurements were chosen because they directly show how safe pedestrians are and how well traffic flows in cities.

Table 1 shows how the proposed system and the old system compare in numbers. The suggested solution cuts down on the time pedestrians have to wait from 45 seconds to 20 seconds. This makes it easier for users and encourages safer crossing behaviour. Real-time pedestrian identification and adaptive signal control also cut the probability of accidents from 35% to 15%, showing how well they work. The time it takes for traffic to clear has also been cut in half, from 60 seconds to 30 seconds. This shows that traffic is moving more smoothly and less congested. Also, edge computing makes the system respond faster, going from 5 seconds to 2 seconds. This is because it lets data be processed and decisions be made faster.

Figure 3 shows the performance comparison in a bar chart. The graphic representation makes it evident that the proposed system is better than the others in every way that was looked at. The fact that waiting time, accident risk, and traffic delay are all going down, while response time is going up, shows that the system does a good job of keeping pedestrians safe and traffic moving smoothly.

Overall, the results show that the proposed IoT-enabled smart zebra crossing system is a better option than traditional fixed-time systems since it is more dependable, flexible, and efficient. This makes it a great choice for use in smart city settings.

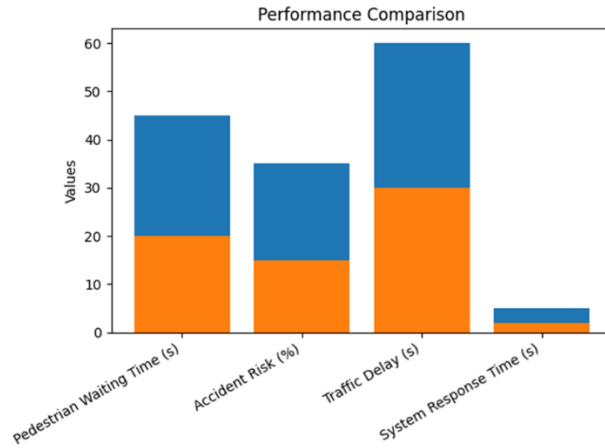


Fig. 3 Performance Comparison.

Table 1: Performance Comparison

Parameter	Conventional System	Proposed System
Pedestrian Waiting Time (s)	45	20
Accident Risk (%)	35	15
Traffic Delay (s)	60	30
System Response Time (s)	5	2

Figures 4–6 give a full visual comparison of the old and new systems. The graphs make it evident that the suggested system makes all performance indicators much better. The improvement graph gives these benefits a number, which shows that the system greatly improves pedestrian safety and traffic flow, making it a great choice for use in a smart city.

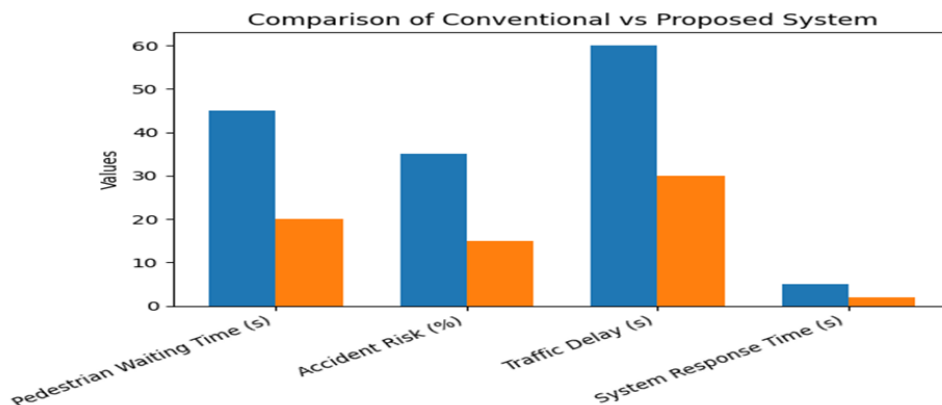


Fig. 4 Comparison of Conventional vs Proposed System

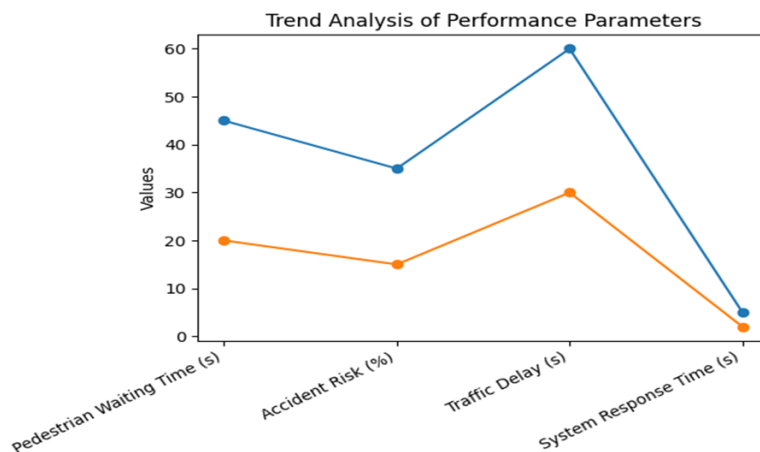
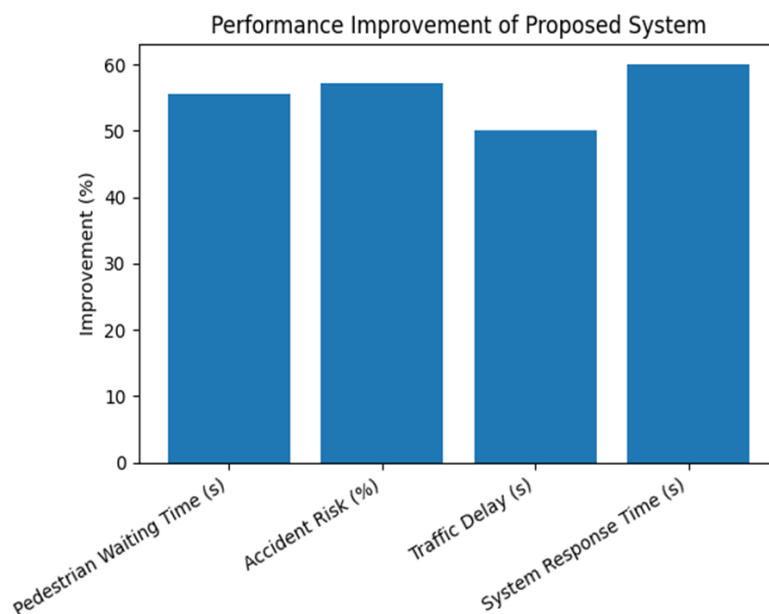


Figure 5: Trend Analysis of Performance Parameters



**Figure 6:** Performance Improvement (%)

## V. Conclusion

This paper presented an IoT-enabled smart automated zebra crossing system that effectively addresses the limitations of conventional fixed-time pedestrian crossing mechanisms. By integrating PIR sensors for real-time pedestrian detection, IP camera-based computer vision for accurate density estimation, and edge computing for low-latency processing, the proposed system achieves intelligent and adaptive traffic control. The trial results show clear improvements in important performance parameters, such as shorter wait times for pedestrians, lower accident risk, less traffic delay, and faster system response. These improvements show that the method works to make pedestrian crossings safer while yet allowing cars to go quickly. Adding IoT makes it much easier to monitor things in real time, make them bigger, and connect them smoothly to smart city systems. The proposed system is a strong, cheap, and scalable way to manage traffic in the current world. Its capacity to change in real time makes it a good choice for use in cities, where it might help make roadways safer and transportation systems more efficient.

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