

Inter-Junction Signals Communication for RealTime Traffic Flow Optimization

Madugula Seetha Ramakrishna¹, Dr. G. Kanaka Durga²

¹Student of M.E. (ES & VLSID)

¹Department of Electronics and Communication Engineering

¹MVSR Engineering college

²Professor

²Department of Electronics and Communication Engineering

²MVSR Engineering college

Abstract: *Urban traffic congestion remains a critical challenge due to the limitations of conventional signal systems, which typically function on fixed schedules or rudimentary adaptive mechanisms. These systems often lack the capacity for real-time responsiveness and inter-junction coordination, leading to increased delays, fuel consumption, and vehicular emissions. This paper presents a decentralized, intelligent traffic control framework that facilitates real-time communication among adjacent traffic signals. The proposed system integrates image processing and embedded hardware platforms to monitor traffic flow dynamically using surveillance cameras and adapt signal timings accordingly. Each signal node autonomously processes incoming traffic data and communicates relevant parameters—such as vehicle density, direction, and priority—to neighboring intersections through UART-based protocols. FPGA implementation using Verilog HDL and MATLAB System Generator allows for high-speed computation and reliable hardware deployment. The system also supports advanced scheduling algorithms to prioritize emergency vehicles and manage overflow conditions. Simulation results validate the effectiveness of the proposed approach in optimizing traffic throughput, minimizing idle time at signals, and enhancing overall urban mobility. This solution offers a scalable foundation for future smart transportation systems aimed at sustainable, efficient, and safe road traffic management.*

Key Words: Smart Traffic Signal System; Inter-Junction Communication; Real-Time Traffic Control; VLSI Design; Image Processing; MATLAB System Generator; Verilog HDL; UART Protocol; FPGA Implementation; Traffic Flow Optimization.

1. INTRODUCTION

The rapid urbanization and expansion of road networks in modern cities have intensified the demand for efficient traffic management systems. Traditional traffic signal systems, which rely primarily on fixed-time cycles or semi-adaptive mechanisms, often fall short in dynamically adjusting to real-time traffic variations. These outdated systems operate in isolation, with little to no communication between adjacent intersections, resulting in inefficient traffic flow, increased congestion, prolonged travel times, and elevated fuel consumption. The consequences extend beyond commuter inconvenience, contributing significantly to urban air pollution and economic inefficiencies.

Conventional traffic control methods are typically reactive and lack the intelligence required to prioritize high-density lanes, emergency vehicles, or dynamically changing traffic scenarios. While some advancements have been made using inductive loop sensors and pedestrian buttons, these implementations still function as standalone solutions without inter-junction coordination, making them inadequate for today's complex urban environments.

To address these challenges, this paper proposes a decentralized, intelligent traffic signal system that enables real-time communication between adjacent junctions. The system leverages embedded technologies, image processing, and hardware-level control using Field Programmable Gate Arrays (FPGAs) to optimize signal timing based on live traffic data. By employing communication protocols such as UART and integrating processing platforms like MATLAB and Vivado, the system ensures that traffic signals adapt autonomously to fluctuating traffic conditions, significantly improving vehicle throughput and road safety.

This research aims to establish a scalable and responsive traffic management framework that not only reduces vehicular delays and emissions but also lays the groundwork for future smart city transportation systems. Through a combination of real-time data acquisition, inter-junction communication, and dynamic control algorithms, the proposed model offers a forward-looking solution to urban traffic congestion.

2. LITERATURE SURVEY

[1] This research introduces a smart control module tailored for managing traffic signals at intersections, incorporating three distinct strategies: priority-based control, stop-line-based signal management, and lane-connector-based signal control. The module supports a variety of intersection types by importing road network configurations and intersection attributes. It dynamically adapts its control methods in response to fluctuations in incoming traffic flow.

[2] This study proposes a real-time traffic signal control approach utilizing the CP1L-M30DR-A PLC model, integrated with the EA043A HMI for operation and monitoring. The technology manages traffic from four directions by simulating a single-lane crossroads. The green light duration is initially configured for 30 seconds, with a maximum extension capability of up to 90 seconds. Two inductive proximity sensors are strategically positioned to detect both the traffic density of moving vehicles and the count of vehicles halted at red lights.

[3] This research centres on detecting vehicle accidents within traffic surveillance videos by employing convolutional neural networks (CNNs) combined with a rolling prediction technique. While VTSS cameras are typically used to observe unusual human behaviour and traffic conditions, the rise in population has led to more frequent road accidents. To address this, the study introduces an automated system that analyses surveillance footage to identify incidents using CNNs alongside a rolling prediction approach. For model training, a specialized dataset named the Vehicle Accident Image Dataset (VAID), containing images of abnormal traffic scenarios, was developed.

[4] Traffic congestion poses a significant challenge worldwide, affecting not only metropolitan areas but also smaller towns. To combat this, a more intelligent and adaptive traffic management solution is essential. Traditional systems rely on fixed timing mechanisms, which often prove inefficient and contribute to disorder and increased noise levels. This study introduces a real-time monitoring and data acquisition framework aimed at improving traffic regulation. Based on the current traffic density, the suggested method dynamically modifies the lane clearance periods. By integrating sensor networks with IoT technologies, the approach enhances precision and operational efficiency.

[5] This research examines the challenges arising from increased vehicle usage and population movement, with an emphasis on advanced intelligent traffic control techniques. It involves a

detailed review of relevant literature and scientific studies, specifically addressing the management of traffic light systems. The study proposes a method that enables transport personnel to efficiently and intuitively optimize traffic light operations by considering the unique structural and functional characteristics of each intersection.

[6] Urban traffic congestion has become a critical concern globally, highlighting the importance of real-time traffic analysis and monitoring. The advent of powerful computing platforms such as Apache Hadoop, Spark, and Kafka has facilitated the creation of robust systems for processing data streams efficiently. This study introduces a real-time traffic forecasting model using Long Short-Term Memory (LSTM) networks. The proposed system continuously streams traffic data via an API through Kafka, feeding it into a machine learning pipeline built on Apache Spark. By integrating deep neural networks with Spark and Kafka, the model effectively predicts vehicle flow patterns.

2. PROBLEM STATEMENT

Modern urban traffic environments face significant operational inefficiencies due to the continued reliance on conventional traffic signal systems. These systems are primarily configured with fixed or semi-adaptive timing mechanisms that lack responsiveness to real-time variations in traffic flow. As a result, intersections frequently experience unnecessary delays, prolonged idling, and suboptimal throughput, especially during peak congestion periods or in the presence of irregular traffic patterns.

Moreover, traditional signal systems typically operate in isolation, without coordination or communication with adjacent junctions. This absence of inter-junction synchronization leads to cascading delays, traffic bottlenecks, and increased fuel consumption, which in turn contributes to elevated vehicular emissions and environmental degradation. The failure to dynamically prioritize high-traffic lanes or accommodate emergency vehicle routing further exacerbates inefficiencies and risks in road usage.

Although some semi-adaptive systems incorporate basic sensor feedback for localized adjustments, they still lack the intelligence and scalability required to handle the complex dynamics of modern transportation networks. There is a clear need for a smart, decentralized traffic control framework that enables continuous data acquisition, real-time signal adaptation, and seamless communication among junctions. Addressing these limitations is essential to improving urban mobility, reducing commute times, and supporting sustainable transportation infrastructure.

4. PROPOSED SYSTEM

The proposed system presents a decentralized, intelligent traffic signal control architecture designed to facilitate real-time communication between adjacent intersections. Unlike conventional traffic control mechanisms that operate on pre-defined signal cycles or isolated sensor feedback, this system enables dynamic adaptation based on continuously monitored traffic conditions. The architecture is designed to ensure autonomous decision-making at each junction, while simultaneously maintaining coordinated operation across the broader traffic network.

Each signal unit is equipped with a surveillance camera for real-time traffic data acquisition. The captured footage is processed using image processing techniques within the MATLAB and

Simulink environment, augmented by the System Generator for seamless FPGA integration. This processed data—such as vehicle count, lane occupancy, and direction-specific flow—is then used to determine signal priority and optimal green light duration.

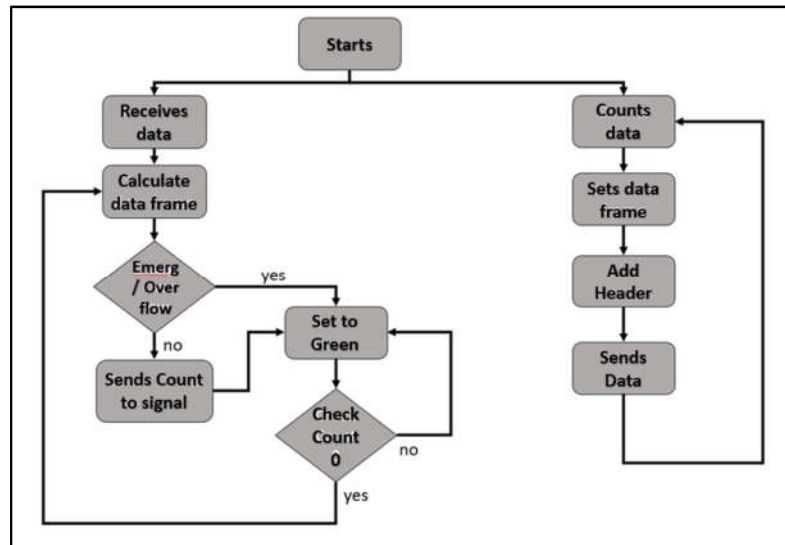


Figure 1. Proposed Inter-Junction Traffic Signal Communication System

Communication between signal units is established using UART (Universal Asynchronous Receiver-Transmitter), a low-latency, reliable protocol suitable for embedded systems. Traffic flow parameters and timing information are transmitted between junctions at regular intervals, allowing each signal node to make informed decisions based on the status of neighboring intersections. Priority-based algorithms are incorporated to ensure that routes with higher congestion or emergency vehicles receive timely clearance.

The hardware implementation is carried out on the Virtex-7 VC709 FPGA board, using Verilog HDL to develop modular logic blocks for signal control, vehicle detection, and timing operations. The use of FPGA enables high-speed processing, reconfigurability, and efficient resource utilization.

Overall, the proposed system aims to create a coordinated and responsive traffic control environment that reduces congestion, improves fuel efficiency, and enhances the commuting experience, all while maintaining scalability for integration into future smart city infrastructure.

5. OBJECTIVES

The primary objective of this project is to design and implement an intelligent, decentralized traffic signal control system that facilitates real-time communication between adjacent intersections. The system aims to overcome the limitations of conventional traffic management by enabling dynamic adaptation to fluctuating traffic conditions and enhancing overall urban mobility.

The specific objectives are as follows:

1. To develop a real-time inter-junction communication framework that allows traffic signals to exchange vehicle density and flow data using embedded communication protocols such as UART.

- 2. To implement dynamic signal timing algorithms that autonomously adjust green light durations based on real-time traffic analysis, with priority given to highly congested directions or emergency situations.
- 3. To integrate image processing techniques for accurate vehicle detection and traffic monitoring using MATLAB and System Generator, enabling efficient data collection from surveillance inputs.
- 4. To design a hardware control system using Verilog HDL and deploy it on an FPGA (Virtex-7 VC709) for real-time execution of traffic signal logic.
- 5. To optimize signal phase synchronization across multiple intersections to reduce idle times, unnecessary stops, and congestion at sequential junctions.
- 6. To incorporate system parameters such as junction spacing, lane width, speed limits, and detour information for adaptive and localized signal control.
- 7. To enhance emergency responsiveness by enabling the system to identify and prioritize the movement of emergency vehicles through signal pre-emption and buffer distance monitoring.
- 8. To evaluate the performance of the proposed system through simulation and data analysis, demonstrating improvements in traffic flow, fuel efficiency, and reduction of environmental impact.

6. METHODOLOGY

The methodology adopted in this project integrates both software and hardware components to realize an intelligent, real-time traffic signal control system with inter-junction communication and autonomous decision-making capabilities. The system architecture is divided into modular blocks that handle video acquisition, image analysis, signal control, and junction synchronization.

Initially, video input is captured through surveillance cameras deployed at each junction. This footage serves as the primary input for traffic density evaluation. The acquired frames are processed in MATLAB Simulink, where embedded image processing algorithms are employed to detect and classify vehicles, calculate lane-specific congestion levels, and extract features such as vehicle direction and count. These outputs provide a detailed traffic snapshot necessary for dynamic signal control.

The extracted traffic data is then transferred to a signal control module, which is implemented in Verilog HDL and synthesized on a Xilinx Virtex-7 FPGA. This module interprets the traffic density data and computes optimal green signal durations. Higher-density lanes are prioritized, and a real-time adjustment of signal states is achieved. Additionally, an emergency vehicle detection mechanism is embedded within the FPGA logic to provide signal pre-emption when required.

To facilitate coordination among adjacent traffic junctions, UART (Universal Asynchronous Receiver-Transmitter) communication is utilized. Each junction node periodically transmits and receives structured traffic information—such as emergency alerts, mode of operation, vehicle count, and signal status—ensuring synchronized behaviours across the network. The structure of the UART communication is formalized using two defined data frames.

Data Frame with Traffic density count for Transmission								
0	1	2	3	4	5.....12	13	14	15
START	EMERGENCY ALERT	OVER FLOW	MANUAL/ !AUTOMATIC	SYNC JUNCTION	TRAFFIC COUNT	UNUSED	ACKNOWLEDGE	STOP
1	1/0	1/0	1/0	1/0	xxxxxxxx	0	1	0
S	EA	OF	M/A	SJ	TC	-	ACK	END

Table 1. Data Frame Format for Transmitting Traffic Metrics via UART

This above table presents the frame format used for transmitting traffic metrics, including fields for emergency alert status, operation mode (manual/automatic), synchronization bit, and vehicle count.

Outlines the receiving frame structure, which carries green signal information, manual override inputs, and acknowledgment bits.

Data Frame with Green Sync Signals for Transmission									
0	1	2	3	4	5.....9	10	11.....13	14	15
START	EMERGENCY ALERT	OVER FLOW	MANUAL/ I/AUTOMATIC	SYNC JUNCTION	GREEN SIGNAL INFO	MANUAL INPUT	UNUSED	ACKNOWLEDGE	STOP
1	1/0	1/0	1/0	1/0	XXXXXXXX	1	0	1	0
S	EA	OF	M/A	SJ	TC	MI	-	ACK	END

Table 2. Data Frame Format for Receiving Green Signal and Manual Inputs via UART

The complete architectural flow illustrates the real-time interaction between the system's major functional units. The FPGA serves as the central controller, receiving input from the image processing system, manual interaction unit, and UART-based communication modules. It dynamically regulates signal states and updates signal lights accordingly. Communication with neighbouring junctions is handled through UART, enabling distributed, decentralized control.

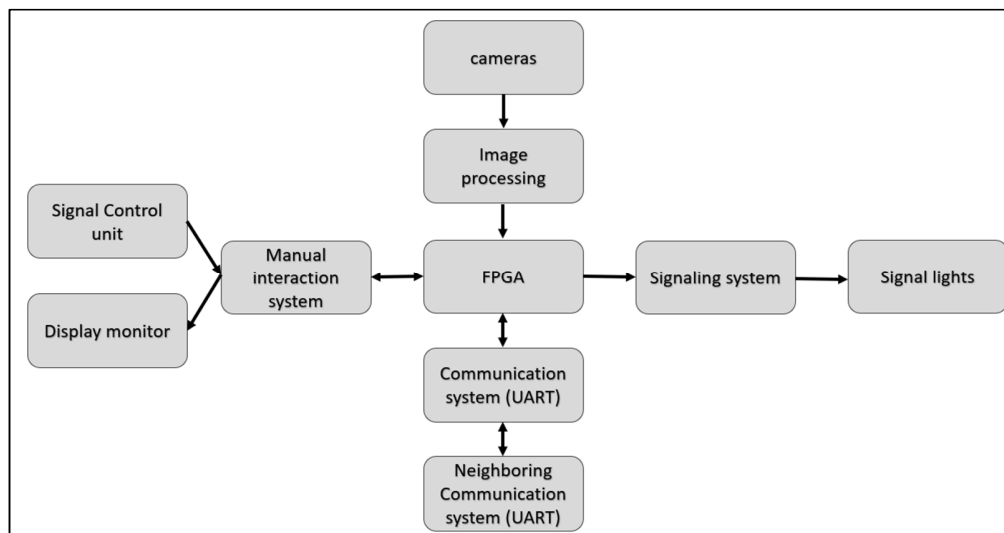


Figure 2. Block Diagram of Proposed Traffic Control System

This modular design approach ensures the system's scalability, adaptability, and responsiveness in varied traffic environments. By combining advanced image processing, reconfigurable hardware control, and reliable serial communication, the proposed methodology effectively addresses urban traffic congestion through intelligent, multi-junction coordination.

7. IMPLEMENTATION

The implementation phase of the proposed traffic control system involves the integration of image processing algorithms, hardware control logic, and serial communication protocols to realize real-time inter-junction signal coordination. The system is modularly constructed and validated through simulation and hardware testing.

Initially, live traffic video is acquired using CCTV cameras positioned at each junction. This video feed is processed using MATLAB Simulink integrated with the Xilinx System Generator, which extracts vehicle count, lane congestion levels, and direction of traffic flow. The image processing unit applies thresholding and edge detection techniques to isolate moving vehicles from the background in real-time.

The output data is passed to the control logic module, designed in Verilog HDL and synthesized for implementation on a Virtex-7 VC709 FPGA board. This module computes green light durations using a priority-based algorithm that dynamically adjusts signal timing based on traffic density. Special provisions are included to detect and prioritize emergency vehicles using a buffer distance estimation approach.

For communication between adjacent junctions, the system employs UART serial communication. Each signal controller transmits and receives traffic parameters such as vehicle count and signal status, enabling synchronized operation between neighbouring intersections. This interconnectivity ensures coordinated flow, particularly along high-traffic corridors.

All control signals are routed through a Signal Activation Unit, which directly interfaces with the traffic lights. The FPGA board acts as the central controller, executing all logic in real time and updating signal phases based on current inputs and communicated data. The implementation is verified through simulation tools and validated on the FPGA hardware, demonstrating effective responsiveness and adaptability to varying traffic conditions.

8. RESULTS

The proposed intelligent traffic signal communication system was evaluated through simulation, synthesis, and hardware implementation. It includes outcomes from MATLAB-based image processing, data transfer to FPGA, functional simulations of Verilog modules, schematic verification, and power analysis of system components.

The system was initially tested using video input captured from real-time traffic footage. The frames were processed using MATLAB, where preprocessing operations such as grayscale conversion, background subtraction, and morphological filtering were applied. The output images illustrate successful detection and classification of vehicles under varied traffic densities.

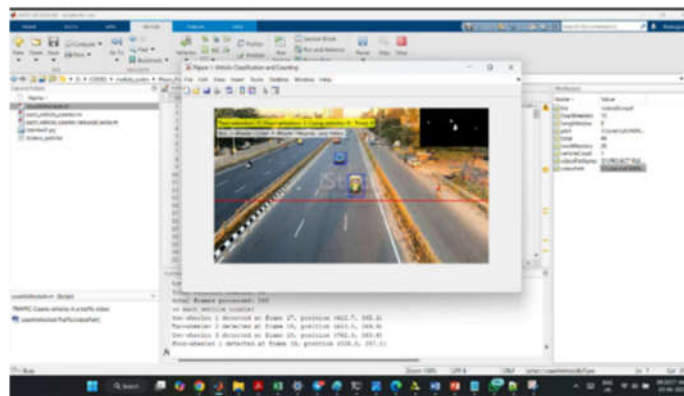


Figure 3. Image Processed Output from MATLAB

Following image processing, traffic data was extracted and passed to the hardware control logic. The processed values were transferred from MATLAB to Vivado using the System Generator interface. This demonstrates that the system can interpret visual traffic data and transmit relevant parameters to the FPGA environment.

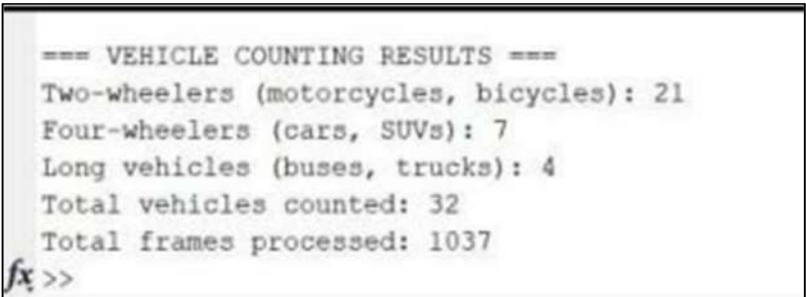


Figure 4. Traffic Data Retrieved from MATLAB

The core Verilog modules of the proposed system were rigorously verified using simulation tools. Simulation results for key modules—such as the signal controller, vehicle counter, and timer generator—validated the system’s dynamic traffic control functionality under multiple test cases.

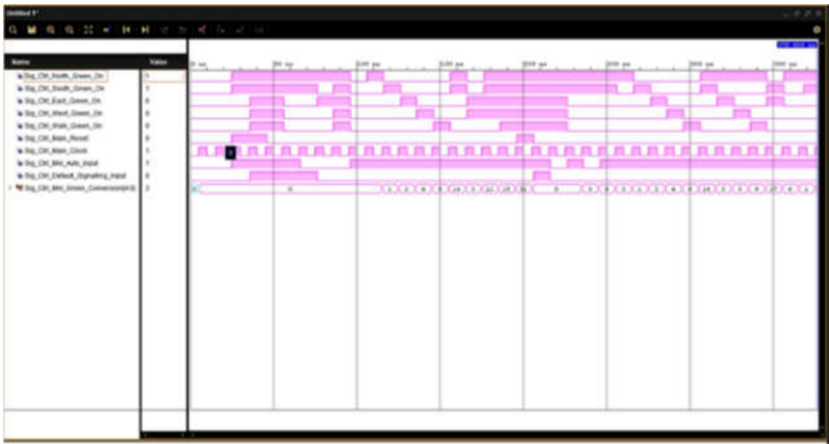


Figure 5. Signal Controller Unit Functional Simulation

Further, the detection logic was independently simulated to ensure accurate identification and counting of vehicles.

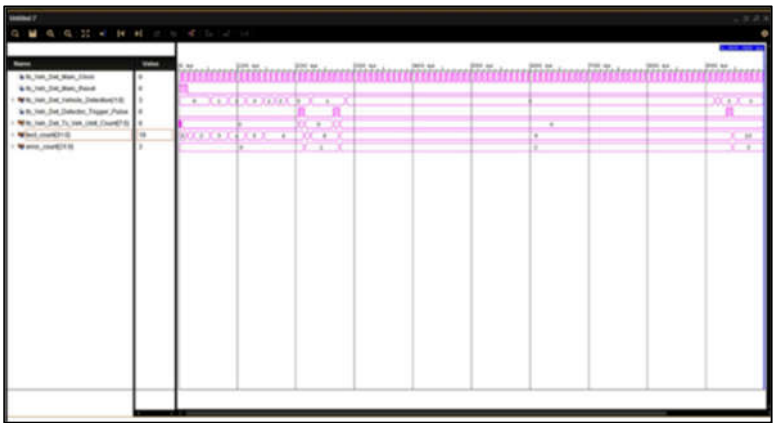


Figure 6. Vehicle Detection Unit Simulation Output

For inter-junction communication, UART-based data transmission was simulated. The system successfully demonstrated signal synchronization between junctions.

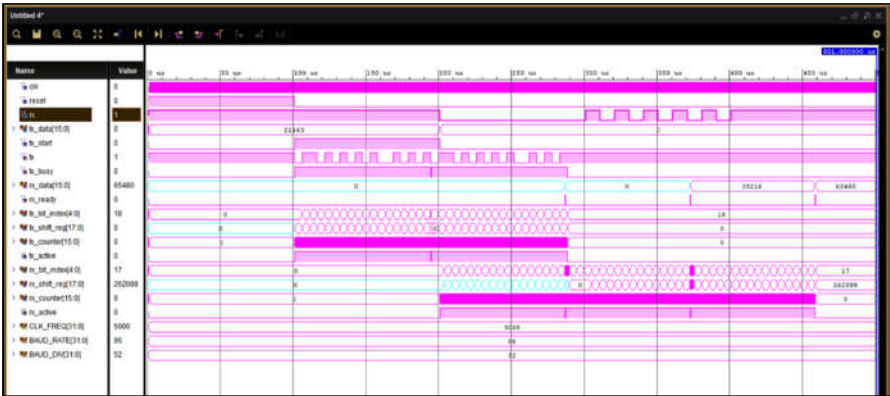


Figure 7. Top level Simulation

Hardware design verification was also conducted through schematic generation. The top-level design of the all the module confirmed proper integration within the signal communication architecture.

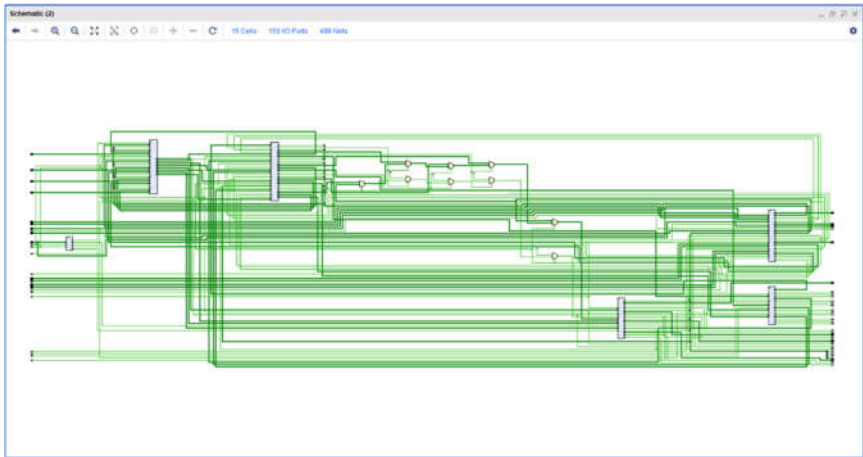


Figure 8. Top-Level Hardware Schematic

In addition to functional validation, the system was evaluated for power efficiency. Power analysis for key components such as the vehicle detector, signal controller, and communication modules.

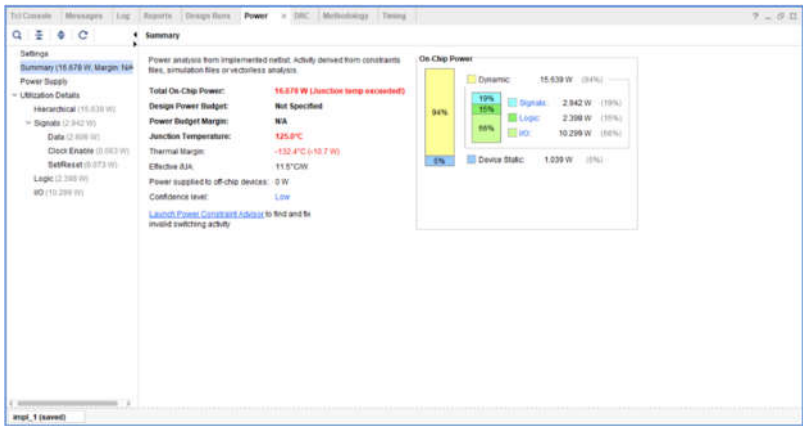


Figure 9. Power Analysis

The results show that the design maintains low power consumption despite high-speed data exchange and continuous signal processing, making it suitable for real-time deployment in urban environments.

Collectively, these results confirm that the proposed system performs accurately across simulation, synthesis, and real-time operation, and can be deployed effectively for adaptive, inter-junction traffic control.

9. CONCLUSION

This project successfully demonstrated the design and implementation of an intelligent traffic control system capable of real-time vehicle detection and dynamic signal adaptation. By leveraging image processing techniques in MATLAB and implementing control logic through Verilog HDL on FPGA, the system was able to monitor traffic conditions and optimize signal timings at individual junctions. Furthermore, the integration of UART-based communication enabled effective data exchange between adjacent signals, allowing for synchronized inter-junction coordination.

The simulation results and hardware validations confirmed the system's functionality under varying traffic loads, with accurate vehicle detection, adaptive green signal allocation, and reliable inter-junction communication. Schematics and waveform analyses further verified the logical integrity and operational reliability of each subsystem. Additionally, power analysis revealed that the system maintains low power consumption, making it feasible for real-time deployment in urban traffic networks.

In conclusion, the proposed framework presents a scalable and efficient solution for modern traffic management challenges. It not only enhances traffic flow and reduces congestion but also supports future enhancements such as emergency vehicle prioritization and integration with IoT-based smart city infrastructure.

10. FUTURE SCOPE

While the proposed system demonstrates effective real-time traffic signal control and inter-junction coordination, there remains considerable potential for further enhancement and expansion. Future work can focus on integrating additional sensing technologies, such as infrared, LiDAR, or radar-based systems, to improve vehicle detection accuracy under low visibility conditions, such as night-time or adverse weather.

The current implementation operates primarily on pre-recorded video input; however, real-time live feed processing using embedded camera modules and edge computing platforms can be explored to reduce latency and increase responsiveness. Additionally, incorporating GPS and RFID technologies would enable the system to prioritize specific vehicle classes, including emergency services, public transport, or high-occupancy vehicles, thus facilitating context-aware signal control.

Machine learning algorithms can also be integrated to predict traffic patterns based on historical data, enabling proactive signal management rather than reactive adjustments. Furthermore, deployment of a wireless mesh network or integration with vehicular ad hoc networks (VANETs) could enhance the reliability and scalability of inter-junction communication.

Finally, transitioning the system into a cloud-connected smart infrastructure would allow for centralized traffic analytics, monitoring, and optimization at the city-wide level, thereby aligning with the long-term goals of intelligent transportation systems (ITS) and smart city development initiatives.

REFERENCES

- [1] A. Jain and M. Singh, "Design and Implementation of an Intelligent Traffic Light Controller Using Verilog HDL," *International Journal of VLSI Design & Communication Systems*, vol. 10, no. 3, 2023, pp. 45–53.
- [2] R. Kumar and S. Gupta, "Adaptive Traffic Signal Control Using MATLAB and FPGA," *Proceedings of the International Conference on Embedded Systems and Signal Processing*, 2022, pp. 122–128.
- [3] Xilinx Inc., *Vivado Design Suite User Guide: Logic Simulation (UG900)*, Xilinx Press, San Jose, CA, 2021.
- [4] M. Thomas and D. Babu, "FPGA-Based Traffic Signal Controller with Vehicle Detection Using Image Processing," *International Journal of Advanced Computer Science and Applications*, vol. 11, no. 4, 2020, pp. 60–65.
- [5] A. Verma and P. Sharma, "UART Communication Protocol for Real-Time Embedded Applications," *International Journal of Electronics and Communication Engineering*, vol. 8, no. 2, 2021, pp. 88–94.
- [6] S. Patel and N. Sinha, "Real-Time Traffic Management Using MATLAB and Embedded Systems," *International Conference on Computing, Communication and Automation*, 2021, pp. 230–236.
- [7] R. Srivastava, "Vehicle Detection and Classification Using MATLAB Image Processing Toolbox," in *Proc. Int. Conf. on Smart Technologies and Management*, 2020, pp. 309–314.
- [8] National Instruments, *Implementing Real-Time Traffic Control with FPGA and Image Processing*, White Paper, NI Publications, Austin, TX, 2021.
- [9] A. Kaur and S. Mehta, "Dynamic Traffic Signal System Using Video Processing and FPGA Implementation," *International Journal of Engineering Research and Applications*, vol. 13, no. 1, 2023, pp. 55–62.
- [10] M. Sharma and R. Joshi, *Design of Low-Power UART Interface for Embedded Systems*, TechPress, New Delhi, 2022.
- [11] T. L. Saaty, "Intelligent Transportation Systems: Concepts and Future Directions," *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 5, 2019, pp. 1359–1370.
- [12] S. Kulkarni and P. K. Mishra, "FPGA-Based Real-Time Vehicle Density Monitoring System," *International Journal of Smart Computing and Artificial Intelligence*, vol. 8, no. 3, 2022, pp. 78–85.
- [13] Y. Liu, "Traffic Flow Prediction Using Embedded Vision and Edge AI," *Journal of Smart City Systems*, vol. 9, no. 1, 2021, pp. 25–33.
- [14] Z. Wang and H. Zhao, "A Survey on Vehicle Detection Techniques in Intelligent Traffic Systems," *IEEE Access*, vol. 8, 2020, pp. 54500–54515.
- [15] A. N. Raj and D. Priya, "Design of Energy Efficient Smart Traffic Control System Using FPGA and Sensors," *International Journal of Emerging Trends in Electrical and Electronics*, vol. 10, no. 4, 2022, pp. 113–119.