Final Project

ABET SO2 Embedded Systems

Design and Validation of a Digital Traffic Light Controller for a High-Flow Urban Intersection

Emilio Ivan Jimenez Lopez

Universidad de las Américas Puebla

26/11/25

Abstract

This work details the design and validation of a digital traffic light controller tailored for the intersection of Prolongación Reforma and Bulevar Aarón Merino in Puebla, Mexico. The project's primary goal is to enhance traffic safety and clarity for both drivers and pedestrians at a high-volume, conflict-prone junction. The controller is based on a finite state machine (FSM) implemented in Verilog, managing four vehicular approaches and a pedestrian crossing, with added support for priority modes and an emergency all-red override. Verification was carried out through simulation and hardware-in-the-loop testing, using an Arduino platform paired with a Python monitoring script to confirm accurate timing, safe phase transitions, and the elimination of conflicting movements. Results demonstrate that the proposed controller satisfies the defined engineering requirements and offers a cost-effective foundation for future smart traffic systems.

1. Identification of Objectives, Requirements, and Constraints

The analyzed intersection presents several critical challenges:

- Intense bidirectional traffic volumes
- Numerous turning movements that create conflict points
- A pedestrian crossing with limited visibility and unclear priority
- Lack of left turn signals despite no rapid transit right of way

Based on these conditions, the following engineering design objectives were established:

- Develop a safe and easily interpretable phase plan for four vehicular approaches and pedestrian crossings with a safe no-vehicle flow stage.
- Prevent simultaneous green signals for movements that conflict, like left turns onto oncoming traffic.
- Ensure minimum and maximum green times reflect observed traffic patterns, or react in real time to traffic data
- Incorporate an emergency mode that sets all signals to red, facilitating emergency vehicle passage or incident management, like car crashes, road invasions, etc.

The design was further constrained by:

- Implementation on an FPGA to facilitate a pipeline to mass production of a chip that can be implemented on any traffic light system
- Operation under a fixed-time cycle (sensors not yet available)
- Adherence to local traffic-signal color conventions and standard safety intervals (yellow and all-red phases)

Together, these objectives and constraints define the technical standards that the controller must achieve.

---

2. Engineering Analysis of the Problem

A systematic evaluation of the intersection was conducted:

- **Traffic flows** were categorized into compatible movements, including through traffic, left turns, and pedestrian phases.
- **Conflict diagrams** were prepared to highlight movements that cannot operate simultaneously.
- **Safety intervals** (yellow and all-red phases) were calculated based on typical approach speeds and the width of the intersection.
- **Cycle time** was selected to balance pedestrian crossing requirements with vehicle queue clearance.

The analysis produced a phase plan consisting of:

- **Two primary opposing vehicular phases** covering through movements and permitted left turns.
- **A protected pedestrian phase**, during which all vehicle approaches to the relevant crosswalk are held on red.
- **An optional priority sub-phase** that allows green time extension for a heavily loaded approach, within predefined limits.

This structured approach ensured that the intersection design was not arbitrary, but firmly grounded in practical traffic engineering principles.

---

3. Development of the Solution

3.1 Controller Architecture

The intersection controller is designed as a finite state machine (FSM) implemented in Verilog. Each state corresponds to a specific signal configuration—combinations of red, yellow, and green indications for the four vehicular approaches, along with the pedestrian signal.

Key design characteristics include:

- Phase grouping: States are organized into distinct phases—Vehicular North–South, Vehicular East–West, Pedestrian, and Emergency.
- Deterministic transitions: State changes are governed by timers that count clock cycles, ensuring predictable operation.
- Configurable parameters: Green, yellow, all-red, and pedestrian walk times are defined as parameters, allowing easy adjustment without modifying the core logic.
- Mode selection inputs: The controller supports multiple modes, including normal operation, priority handling, and emergency response.

3.2 Hardware-in-the-Loop Validation Setup

To extend validation beyond simulation, the FSM design was tested in a hardware-in-the-loop environment:

- The Verilog FSM was synthesized and deployed onto an FPGA-compatible development board.
- Six digital output lines were used to encode the current state.

- An Arduino read these outputs, reconstructed the state, and transmitted the data via serial communication to a computer.
- A Python script decoded the incoming messages and displayed the active signals and timers in real time, effectively simulating a virtual intersection.

Summary

This validation methodology provides a structured, step-by-step approach that accounts for practical constraints such as finite clock frequency, limited I/O availability, and microcontroller processing capabilities.

4. Evaluation of the Solution

The controller design was systematically verified against the initial specifications:

1. **Safety and Conflict-Free Operation**
   - Simulation waveforms and real-time monitoring confirmed that no conflicting movements were ever active simultaneously.
   - All phase transitions correctly incorporated yellow and all-red intervals to ensure clearance.
2. **Timing Accuracy and Sequence Integrity**
   - Timer values were validated in both simulation and hardware, with deviations limited to a single clock cycle.
   - The pedestrian phase consistently enforced the minimum walk duration before control returned to vehicular traffic.
3. **Priority and Emergency Handling**
   - In priority mode, the designated approach received extended green time only up to a safe upper bound, after which the system reverted to the normal sequence.

- Activation of the emergency input triggered an immediate transition to the all-red state, which was maintained until the emergency signal was cleared.

4. **System Robustness**
    - The FSM was subjected to varied activation sequences of priority and emergency inputs. No deadlocks or undefined states were encountered.

Across all operating modes—normal, priority, and emergency—the controller was shown to meet the defined requirements, ensuring safe, reliable, and specification-compliant performance.

---

5. Sustainability Considerations

Although the current controller operates on a fixed-time basis, several sustainability dimensions were integrated into its design:

1. Social Sustainability

- A dedicated pedestrian phase with exclusive right-of-way enhances safety for vulnerable users and promotes walking as a viable mode of transport.
- Clear and predictable signal sequences reduce uncertainty and discourage risky behaviors such as red-light violations.

2. Environmental Sustainability

- Coordinated, conflict-free movements minimize unnecessary stops, thereby reducing vehicle idling and associated emissions, particularly during peak traffic periods.
- Implementation on a low-power digital platform ensures minimal energy consumption by the controller itself.

3. Economic Sustainability

- The system leverages inexpensive, widely available hardware, lowering deployment costs for municipalities.

- Its modular FSM architecture and parameterized timing values simplify maintenance and upgrades, requiring only configuration adjustments rather than full redesigns.

Future Directions

The same architecture can be extended with sensor integration and adaptive timing strategies, aligning with the **UN Sustainable Development Goals** for sustainable cities and communities.

---

6. Conclusions and Future Work

A digital traffic light controller for a complex urban intersection was successfully **designed, implemented, and validated**.

The project achieved the following:

- **Defined clear objectives and constraints** rooted in safety, signal legibility, and hardware limitations.
- **Applied systematic engineering analysis** to establish a conflict-free phase plan and timing scheme.
- **Implemented an FSM-based solution in Verilog**, supported by a hardware-in-the-loop validation platform.
- **Verified performance against specifications**, confirming stable and safe operation under normal, priority, and emergency modes.
- **Incorporated sustainability considerations**—social, environmental, and economic—demonstrating potential contributions to safer and more efficient urban mobility.

Future Work

Planned extensions include:

- Integration of vehicle and pedestrian detection systems.

- Implementation of adaptive timing strategies.
- Exploration of coordination with adjacent intersections to establish a simple **green-wave corridor**.

References

Chekurkov, I. D., & Hristov, K. H. (2025). *Design and Implementation of an Adaptive FPGA-Based Traffic Light Control System Using Verilog.* Proceedings of the 60th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST), 1–4.

Koirala, N., & Srivatanakul, T. (2025). *Smart Traffic Light Control System with Emergency Vehicle Detection and Boom Barriers Using Arduino.* IEEE Conference on Technologies for Sustainability (SusTech), 1–5.