Materials Research Proceedings 64 (2026) 469-476 https://doi.org/10.21741/9781644904091-59

FPGA-Based Mine Traffic Controller with Pedestrian and Machinery Prioritization

Hajar SADOK[1,a *], Ahlam MOUSSA[1,b], Ilham NAIT HIM[1,c] and Moulay El Hassan EL AZHARI[1,d]

[1]Al Akhawayn University in Ifrane, Avenue Hassan II, Ifrane 53000, Morocco

[A]H.Sadok@aui.ma, [b]Ah.Moussa@aui.ma, [c]I.NaitHim@aui.ma, [d]M.ElAzhari@aui.ma

Keywords: FPGA Traffic Control, Underground Mine Safety, Finite State Machine (FSM), VHDL, ALTERA Board

Abstract. Underground mining is one of the most dangerous industrial settings, due to its inadequate lighting, limited infrastructure, and management of both pedestrian and machinery traffic flow through narrow tunnels. To enhance safety at the intersection of mining vehicles and miners, this paper presents the design and simulation of an FPGA-based traffic control system. The design is highly optimized, occupying less than 1% of the board's logic fabric, and it is implemented using VHDL. The model relies on a Finite State Machine (FSM) that governs two crossing paths, one for mining machinery and another for mining pedestrians. Default priority is assigned to the mining vehicles, and, upon request, miners are granted timed access. To simulate extreme cases, an emergency override functionality is applied, such that it halts all traffic to prioritize evacuation, and the system employs 7-segment displays and LEDs for countdown timers and status display. The maximum response time for the state transitions is a mere 20 ns, verified through Quartus simulation of the traffic control design. The latter is additionally validated in Proteus, which further confirms the solution as a reliable approach to real-time mine traffic control.

Introduction

While not being among the largest contributors to the world of industry and employment, mining presents a large source of fatal injuries in private industries, which is roughly four times the average rate. In 2021, the fatal injury rate for mining was 14.2 per 100,000 full-time workers, compared to 3.8 overall in private industry [1]. Poor visibility, limited space, and inadequate real-time traffic control at traffic crossings of a mine are particularly vulnerable to accidents [2]. In such high-risk environments, the conventional control and signaling systems may not suffice, and the most traditional sense of control is likely to fail under emergency conditions, such as fires and evacuations [3].

To reduce these risks, the use of smart embedded systems for real-time decision-making is at the top priority. Microcontrollers are common in the above ground systems used to control and manage traffic lights. For instance, ATmega32 AVR with infrared sensors can provide this function [4]. Field-Programmable Gate Arrays (FPGAs) provide a powerful framework on which a smart traffic control can be developed. They are reconfigurable, have low latency, and can operate in parallel with one another [5]. The implementation of safety-critical systems in mine traffic control is possible with complex logic implemented using VHDL (VHSIC Hardware Description Language) and FSMs.

This paper proposes a simple yet robust mine traffic control system. It provides mining vehicles with default priority whilst accommodating pedestrian crossings upon request or detection. The system also includes an emergency override state that halts both pedestrian and vehicle crossing when called. The logic design is simulated in Quartus and visualized in Proteus, as well as on the

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 license. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under license by Materials Research Forum LLC.

Materials Research Proceedings 64 (2026) 469-476 https://doi.org/10.21741/9781644904091-59

FPGA board for further validation, where utilizes seven-segment displays and LED indicators for intuitive feedback, thus reducing the risk of mine accidents.

Methodology

System Architecture and Modules. As shown in Fig. 1, the proposed mine traffic control system was modularly developed, centered on a Finite State Machine (FSM) as the central controller. The latter handles all inputs to determine the state of the system according to its Priority Logic ran concurrently on the Altera DE2-115 FPGA board, which results in a predictable and reliable system for mine traffic safety.

As part of the FSM inputs, pedestrian requests and emergency signals are controlled, with the Priority Logic giving default passage to mining vehicles. The Priority Logic relies on a timing module, consisting of 12-bit ripple counters that generate count downs and safety delays, while LEDs, a seven-segment display, multiplexers (MUXs), and a decoder are used for state display. By adopting this structure, pedestrian and emergency requests are safely and quickly handled.

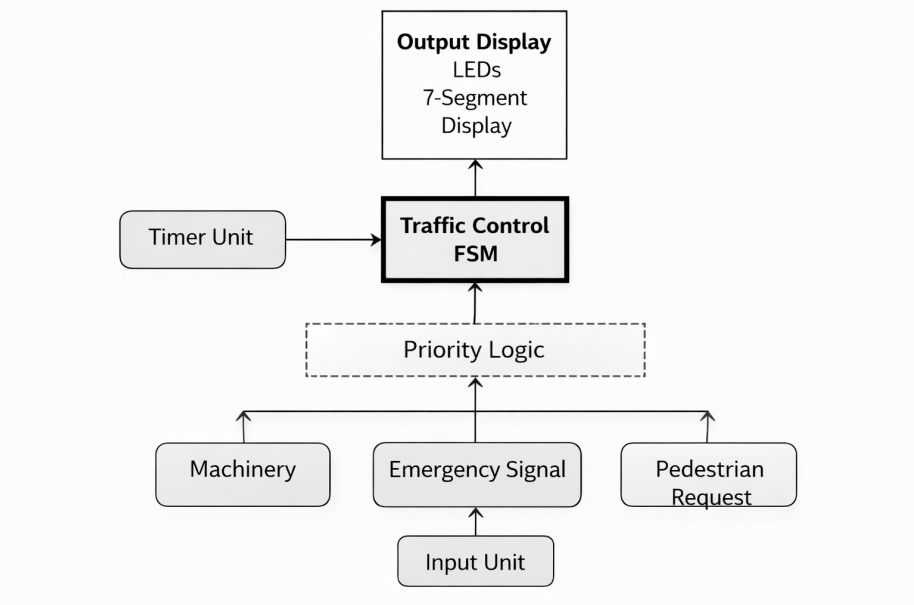


Fig. 1. Architecture diagram of the proposed mine traffic control system

Identification Tags and Proximity Sensing. In the modern mining industry, miners and mining vehicles are equipped with identification tags (e.g, RFID, or BLE beacons) [6]. These tags are identified by fixed sensors (anchors) placed at road intersections to detect their signals, calculate their proximity, and identify whether they belong to a miner, a mining vehicle, or an emergency vehicle.

Furthermore, the traffic controller automates safety and enhances it by using these tags and anchors. For instance, the system can detect miners' tags and automatically prepare for pedestrian crossings, eliminating the need for a miner to manually request crossing. In addition, anchors can also recognize emergency vehicle tags and spontaneously clear the path for priority passage. Beyond real-time control, this setup also serves as a digital audit keeping track of the tag entering or exiting intersections, allowing for safety monitoring.

Traffic Control FSM and Priority Logic. The FSM operates through five main states. The *Idle (IDLE)* state is the default mode, where no pedestrian requests are active, and vehicles are given priority. In the *Vehicle Go (Vehicle_Green)* state, the vehicle path remains open while pedestrian requests are either pending or inactive. When a pedestrian initiates a crossing request, the system enters the *Pedestrian Request (Pedestrian_rep)* state, signaling the need to clear vehicles from the crossing area. Once it is safe, the *Pedestrian Go (Pedestrian_Green)* state is activated, allowing

Materials Research Proceedings 64 (2026) 469-476 https://doi.org/10.21741/9781644904091-59

pedestrians to cross while a countdown timer displays the remaining crossing time. Finally, the *Emergency (EMG)* state overrides all others, stopping all traffic except for predefined emergency vehicles, which are identified through their unique tags.

Transitions between the FSM states are based on real-time input signals. The *Pedestrian_Req* signal is activated when a pedestrian pushes the request button, activating the countdown timer and stopping the mining vehicle traffic flow. On the other hand, the *EMG* signal is sparked by the emergency trigger, immediately overriding all current states. These transitions are shown in the flowchart in Fig. 2.

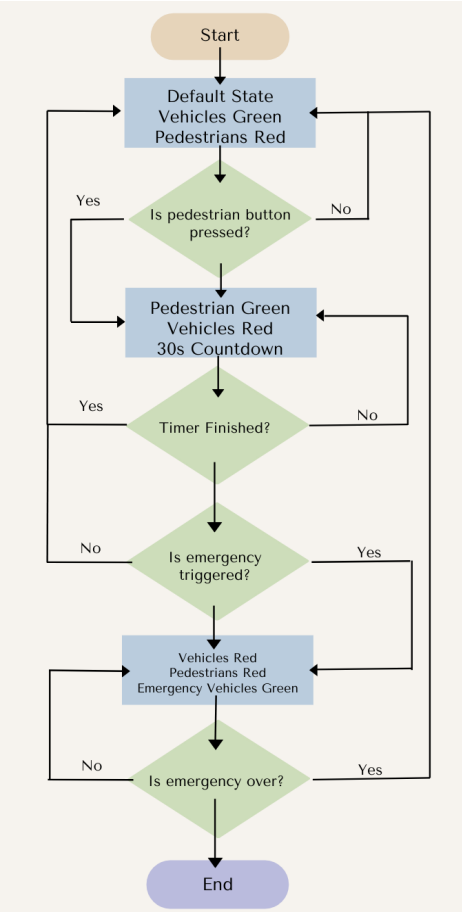


Fig. 2. FSM Transitions flowchart

FPGA Hardware Implementation. The physical implementation of the traffic controller used VHDL logic, developed and synthesized in Quartus II (13.1) design suite, and tested on the Altera DE2-115 FPGA. Unlike a microcontroller, which typically executes one instruction at a time, the parallel operation allowed by the FPGA architecture allows the different signals of the FSM and its priority logic to operate in their own logic units simultaneously, thus reducing latency and jitter [7]. The internal 50 MHz clock of the board powers the safety delays and aligns the onboard LEDs and 7-segment displays for real-time visual feedback. This hardware approach, instead of software-dependent microcontrollers, avoids bottlenecks, lagging, and system crashes, critical to underground mining safety.

Display and Decoder Logic. The 7-segment decoder was implemented using VHDL logic, following truth tables and Karnaugh maps (K-maps), where each binary input *ABCD* is mapped to the corresponding 7-segment representation (a, b, c, d, e, f, g) in active-low logic (logic 0 turns a segment ON).

The truth table behind the active-low 7-segment display representation is presented in Table 1.

Materials Research Proceedings 64 (2026) 469-476 https://doi.org/10.21741/9781644904091-59

Table 1. Active-Low 7-segment display truth-table

HEX	DCBA	a	b	c	d	e	f	g
0	0000	0	0	0	0	0	0	1
1	0001	1	0	0	1	1	1	1
2	0010	0	0	1	0	0	1	0
3	0011	0	0	0	0	1	1	0
4	0100	1	0	0	1	1	0	0
5	0101	0	1	0	0	1	0	0
6	0110	0	1	0	0	0	0	0
7	0111	0	0	0	1	1	1	1
8	1000	0	0	0	0	0	0	0
9	1001	0	0	0	0	1	0	0
A	1010	0	0	0	1	0	0	0
B	1011	1	1	0	0	0	0	0
C	1100	0	1	1	0	0	0	1
D	1101	1	0	0	0	0	1	0
E	1110	0	1	1	0	0	0	0
F	1111	0	1	1	1	0	0	0

For each segment (a-g), a Karnaugh Map (K-Map) is constructed from the truth table, and used to derive a minimized Boolean expression, all of which are implemented in a VHDL process to control each segment output ($F_a \; to \; F_g$). The decoder converts a 4-bit binary input to a decimal digit displayed on the 7-segment display, enabling the countdown functionality. As an example, the expression of segment F_a be derived as from the K-Map in Table 2:

Table 2. K-map for segment F_a

	00	01	11	10
00	0	1	0	0
01	1	0	0	0
11	0	1	0	0
10	0	0	1	0

$$F_a = \left(B \cdot \overline{D}\right) + \left(A \cdot \overline{C}\right) + \left(\overline{B} \cdot \overline{C} \cdot \overline{D}\right). \quad (1)$$

The other segment expressions can be similarly derived. As for the decoder, it is essential to provide visual feedback, such as the countdown when pedestrians are crossing or when an emergency is detected, thus ensuring real-time intuitive feedback for the miners.

Results and Discussion

The VHDL logic was first synthesized and simulated in Quartus to verify functional correctness. The system was then validated on the FPGA board to simulate the traffic scenarios and verify the FSM transition states under idle, pedestrian request, and emergency conditions.

Quartus Simulation. The design was first implemented as a VHDL in Quartus II 13.1. Each FSM state and transition was represented using the same controlled input variables mentioned in the system architecture section. To test the validity of the program, a VWF (Vector Waveform File) was generated in Fig. 3. The latter clearly showed the correct transitions between states, synchronizing counters, and the behavior of outputs with a delay.

Materials Research Proceedings 64 (2026) 469-476 https://doi.org/10.21741/9781644904091-59

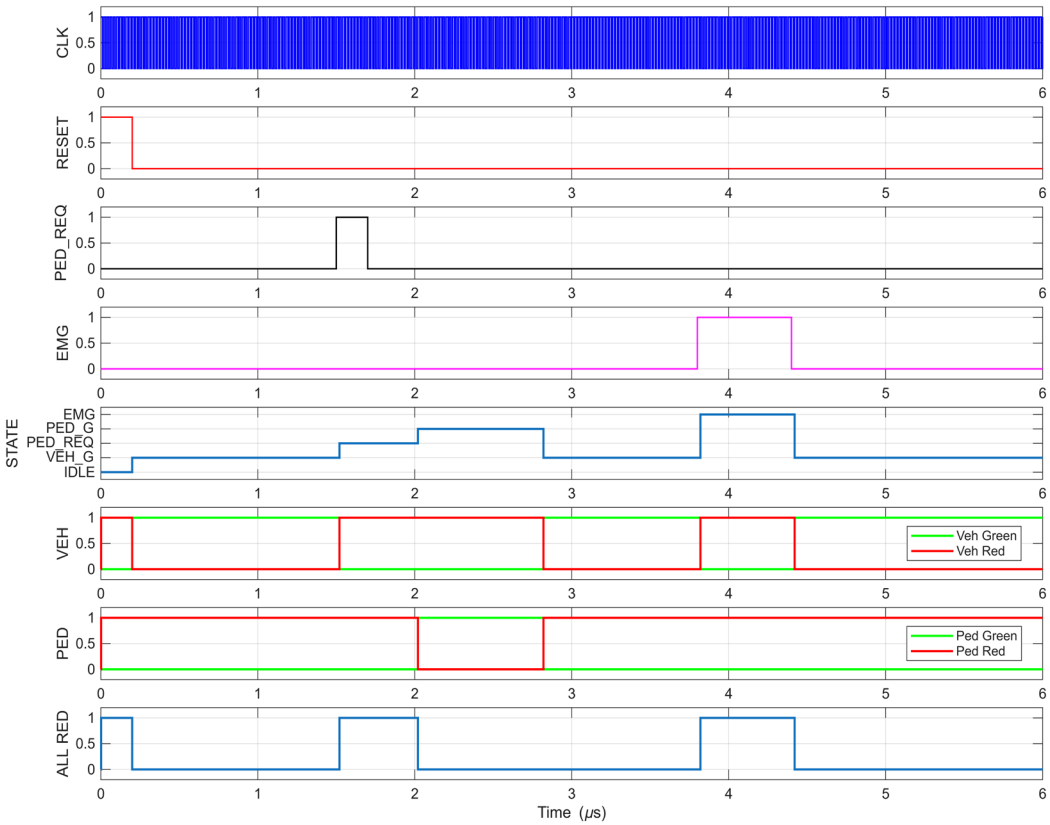


Fig. 3. Waveform of the simulated traffic control program

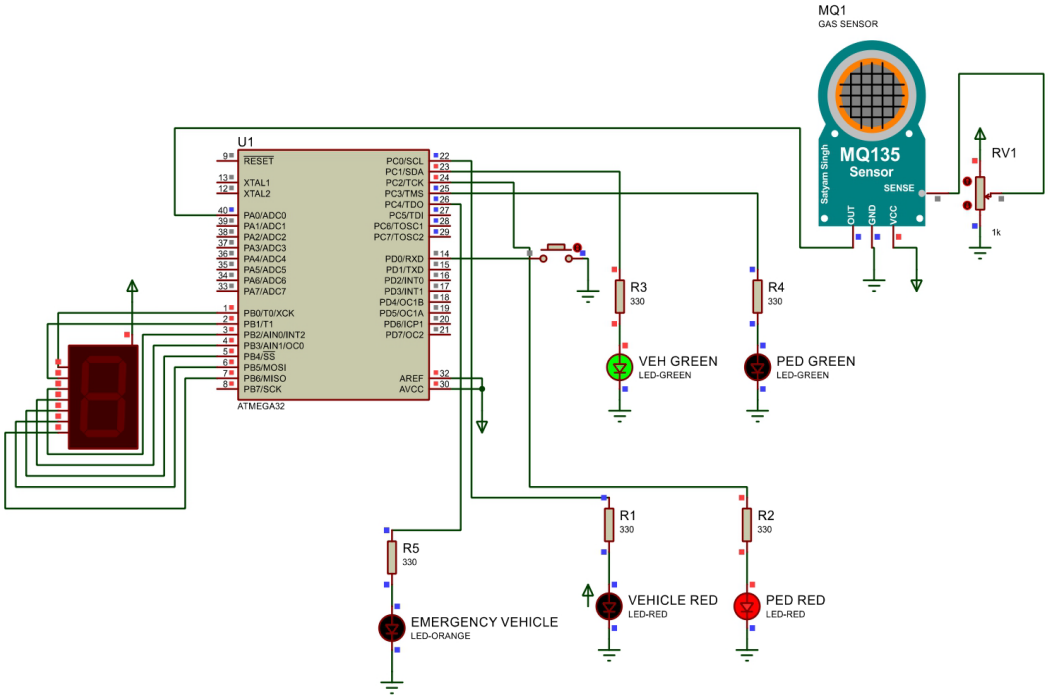
Particular attention was given to the emergency state, ensuring that traffic was halted while predefined emergency vehicles only were active.

Timing diagrams confirmed the accuracy of countdown behavior using ripple counters. However, the delay in Quartus does not align with the Altera board one, leading to the observed waveform, despite the accuracy of the board operation.

Proteus Visualization. The proposed logic was evaluated in the Proteus software in order to visualize the real-time behavior of the system. An ATmega32 microcontroller was used, and a push-button was linked to the pedestrian' request. Moreover, a gas sensor was used to simulate emergency triggers, especially relevant in the mining industry. Red and Green LEDs symbolized the position of both the vehicles and the pedestrian crossing, and the countdown was also programmed to give a crossing time of 5 to 0.

The system ran as aimed when the simulation was run, even in the Idle State which is observed in Fig. 4, and automatic reset to vehicle priority which follows the pedestrian crossing and emergency override states. The effectiveness and ease of use of the traffic control system was also confirmed by the success of this simulation, and the visual indicators that were of particular importance in the limited lighting conditions of normal underground tunnels.

Materials Research Proceedings 64 (2026) 469-476 https://doi.org/10.21741/9781644904091-59



ã

Fig. 4. Proteus simulation of the traffic control - Idle State

Hardware Visualization. Finally, the ALTERA DE2-115 board was used to synthesize and implement the full FSM design. Each FSM state was represented by an LED, and the 7-segment display showed the pedestrian crossing countdown timer set to 30 seconds. Both the pedestrian request and the emergency trigger were simulated using pushbuttons on the board.

To verify the core states, the idle state was first observed, in which vehicles had the default priority, and pedestrians were stopped from crossing. Next, the pedestrian request allowed the pedestrians to cross for 30 seconds, displayed on the countdown, whilst vehicles were stopped, as seen in Fig. 5. Lastly, the emergency trigger stopped both vehicles and pedestrians from crossings, allowing only emergency vehicles the right of passage.

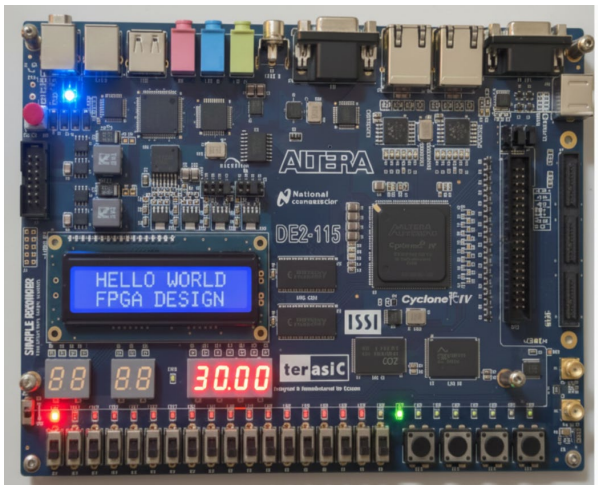


Fig. 5. DE2-115 board pedestrian request state

Performance Metrics and Analysis. The VHDL implementation showed efficient pin requirements, leveraging less than 1% of the available pins on the ALTERA board. Additionally,

by utilizing the internal 50 MHz oscillator, the system maintains a response time of 20 ns for state transitions, including the emergency response time, given by the clock period.

By contrast, standard microcontrollers tend to operate at lower frequencies, requiring more cycles, interrupt handling, and ultimately larger response time (e.g., ATmega32 operates at a maximum frequency of 16 MHz).

Discussion and Potential Deployment. The proposed FPGA-based system offers reliable, real-time traffic control that is also energy efficient. Its hardware-based FSM, in contrast to software-based solutions, guarantees low power usage, and its modular architecture can be extended to a highly scaled deployment with comparatively little extra energy investment. The system can be used with the support of micro-power sources, which can be integrated into the system, contributing to its autonomous operation, energy efficiency, and sustainability.

Distinctive Features. In contrast to existing FPGA-based mine traffic systems, which either adhere to predetermined signal sequences or do not consider environmental hazards [8, 9], the proposed design is a single, unified, FSM with built-in priorities that directly wires RFID and BLE sensors, rendering it a safer, more comprehensive, and automatic system.

System Limitations. Currently, the system is limited to a simple two-way (vehicle/pedestrian) setup. However, despite the plentiful internal logic of the FPGA board, it only has a limited number of I/O pins, thus limiting the number of intersections the board can wire. Additionally, in real mines, the anchors and the FPGA board might be very far apart, leading to a voltage drop that might require extra hardware like signal repeaters.

Furthermore, underground mines tend to have humid and dusty environments, which would affect the FPGA board unless provided with industrial closures following the IP67 rating. The heavy machinery correlated with underground mining practices (e.g., continuous drilling) also leads to mechanical stress and vibrations, that may even cause cracks on the FPGA.

Conclusion and Future Work

The proposed system of traffic control of underground mines using FPGA that guarantees the security of pedestrian crossings provides valid results. The system had real-time functionality, which was successful with a high level of energy efficiency and flexibility. It was designed in VHDL, simulated in Proteus and Quartus, and executed on an ALTERA DE2-115 board.

Future studies will be focused on the expansion of tag-based monitoring to enhance automation, machine learning to enable adaptive timing and predictive safety analytics [10, 11], and sustainable energy-aware operation [12, 13]. With the integration of lightweight machine-learning models, the system would be more intelligent and context-aware with regard to traffic control and dynamically adjust pedestrian crossing times and default priority.

Declaration of use of AI-Assistance in the Writing Process

The authors acknowledge the use of generative artificial intelligence (AI)-assisted technologies in the preparation of this document. In particular, ChatGPT, developed by OpenAI, was used as an editorial and linguistic tool. The authors have full ownership of the technical content, analysis, interpretations, and conclusions presented in this work.

References

[1] Bureau of Labor Statistics, Mining fatalities rose 21.8 percent from 2020 to 2021 (2023). https://www.bls.gov/opub/ted/2023/mining-fatalities-rose-21-8-percent-from-2020-to-2021.html

[2] C. Andersson, Predictive model for traffic control in underground mines, DIVA (2019). https://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-75964

[3] F. Javaid, A. Wang, M.U. Sana, A. Husain, I. Ashraf, An Optimized Approach to Channel Modeling and Impact of Deteriorating Factors on Wireless Communication in Underground Mines, Sensors 21 (2021) 5905. https://doi.org/10.3390/s21175905

[4] W. Kleitz, Digital Electronics: A Practical Approach with VHDL, ninth ed., Pearson, 2011.

[5] M.S. Arifin, S.A. Razi, A. Haque, N. Mohammad, A Microcontroller Based Intelligent Traffic Control System, Am. J. Embed. Syst. Appl. 7 (2019) 21-25. https://doi.org/10.11648/j.ajesa.20190701.1

[6] Smart Tracking and Monitoring in Supply Chain Systems using RFID and BLE, IEEE Conf. Publ. (2021). https://doi.org/10.1109/ICSPC51351.2021.9451700

[7] Boosted genetic algorithm using machine learning for traffic control optimization, IEEE J. Mag. (2021). https://doi.org/10.1109/TITS.2021.3066958

[8] A. Didal, P. Sachan, A. Katiyar, P. Gautam, Traffic Light Controller, Int. J. Eng. Tech. Res. 2 (2014).

[9] Unmanned driving technology in coal mine based on semantic information method, IEEE J. Mag. (2023). https://doi.org/10.1109/ACCESS.2023.3257574

[10] D. Fister, A. Jakopič, M. Truntič, Control Applications with FPGA: Case of Approaching FPGAs for Students in an Intelligent Control Class, Appl. Sci. 15 (2025) 12884. https://doi.org/10.3390/app152412884

[11] Adaptive Fault-Tolerant control of platoons with guaranteed traffic flow stability, IEEE J. Mag. (2020). https://doi.org/10.1109/TVT.2020.2990279

[12] PSIM-based modeling of automotive power systems: conventional, electric, and hybrid electric vehicles, IEEE J. Mag. (2004). https://doi.org/10.1109/TVT.2004.823500

[13] An RFID electronic tag based automatic vehicle identification system for traffic iot applications, IEEE Conf. Publ. (2011). https://doi.org/10.1109/CCDC.2011.5968962