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Design and implementation of smart traffic light controller with emergency vehicle detection on FPGA

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ABSTRACT

Increased traffic volumes resulting from urbanization, industrialization, and population growth have given rise to complex issues, including congestion, accidents, and traffic violations at intersections. In the absence of a functional smart traffic light system, traffic congestion occurs due to imbalanced traffic flow at intersections. Current traffic management lacks provisions for ensuring the unobstructed movement of emergency vehicles, even a small delay for which can have significant consequences. This paper presents a smart traffic light controller developed using Verilog hardware description language (HDL) in Quartus Prime 21.1 and Questa Intel field programmable gate array (FPGA) Starter Edition 2021.2, and implemented on an Altera DE2-115 FPGA. The controller is designed specifically to detect emergency vehicle at four-way intersections for inputs radio frequency identification (RFID) readers and infrared (IR) sensors. The RFID readers and IR sensors are managed through slide switches on the FPGA board. The smart traffic light controller contains three sub-modules: clock division, counter, and finite state machine (FSM) operation, enabling it to manage traffic in scenarios with emergency vehicles, high traffic density, and low traffic density. This proposed system can alleviate intersection congestion by controlling access and allocating time effectively. In conclusion, the project ensures the smooth passage of emergency vehicles by continuously monitoring their presence and giving them priority in traffic flow.

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1. INTRODUCTION

Traffic has increased dramatically because of urbanisation, industrialisation and population development. According to Malaysia Transportation Statistics 2022, total number of land transportation in Malaysia for year 2022 is recorded as 35,092,737 [1]. In Malaysia, land transportation includes motorcycles, cars, buses, taxis, lorries and other vehicles including emergency vehicles [1]. Traffic lights play a crucial role in traffic control. Traffic lights are signaling devices that are positioned at intersections and used to manage the flow of traffic on the road [2], [3]. The vast majority of traffic lights worldwide run on a predefined timed circuit [2]. Vehicles on the red light side must occasionally wait for the green light even there is little or no traffic. It leads in a waste of valuable time. Ambulances, fire trucks and police patrols among others cannot afford to lose time waiting at traffic lights. With the increase in traffic comes the emergence of a slew difficulties such as traffic congestions, accidents and violations of traffic rules at busy intersections. Congestion is a major issue in many places throughout the world today. Traffic congestion is a major element in the delay in the utilisation of emergency vehicles [4], [5]. This type of traffic congestion was most common near traffic light intersections [4], [5]. Congestion develops when there is no functioning smart traffic light controller system. The problem arises as a result of an imbalance in traffic circulation at the crossings resulting in substantial congestion in the affected directions [6]. The existing traffic management method does not include a provision for guaranteeing the smooth passage of emergency vehicles [7].

These emergency vehicles require a system that will allow them to cross the traffic lights safely and without delay [8]. Badiruzaman *et al.* [8] published a research article that reviews the performance of emergency response teams (ERT) in Malaysia. Existing emergency vehicle priorities system in Malaysia unable to alleviate traffic congestion issues [8], [9]. The article put forward a recommendation to enhance the emergency response system, with the goal of aiding emergency providers in meeting international standards for emergency response times [8]. The issue of emergency vehicles being obstructed may be avoided by establishing a traffic light system that has the capability of detecting emergency vehicles and controlling the traffic light conditions. There are a lots of research on the traffic light controller investigated for multiple junctions traffic light such as three-junctions (T-junction) [10]–[12] and four-junctions [13]–[19].

In 2021, Shamsuddin *et al.* [20] published a research paper about traffic light controller (TLC) using DE-10 Nano integrated with ESP 8266 Wi-Fi module for internet of things (IoT) implementation. The controller detects emergency vehicle using audio and video, while emergency vehicle driver can view the intersection status using Blynk Apps to guide driver either save to pass through the intersection or not. However, the details on how the audio and video detection for emergency vehicle is not clearly presented. Han and Lin [21] has developed an intelligent traffic light controller (ITLC) using Verilog hardware description language (Verilog HDL) that saves time by dispersing signal timing based on road width. However, there is no provision to detect the presence of an ambulance to ensure smooth ambulance transportation. Dilip *et al.* [22] developed an innovative traffic light controller based on field programmable gate array (FPGA) that controls traffic lights based on traffic density. This paper, however, does not provide an acceptable duration for the green signal depending on the density. A condition for two or more roads have the same volume of traffic was not fully considered. Sabri *et al.* [6] has created a traffic light controller system that utilises FPGA technology to control and allocate effective periods of time to various users with the goal of reducing or eliminating difficulties at junctions. The system represents a slight advance over the current basic fixed-time approach traffic light controller, it only converts to a flexible-time based traffic light. Singh and Daniel [23] created an FPGA implementation of a 24-hour advanced traffic light controller system based on road intersection congestion. However, the technology to detect traffic and allocate time for each signal at traffic lights was not presented. The time zone is also based on assumptions.

Humayun *et al.* [24] introduced an emergency vehicle management solution (EVMS) that utilizes IoT sensors, GPS, 5G, and cloud computing to determine an efficient vehicle-passing sequence, prioritizing emergency vehicles at junctions to minimize delays while minimizing the impact on regular traffic. Hosseinzadeh *et al.* [25] presents a traffic control scheme, with both centralized and decentralized approaches. The research aimed at mitigating congestion in a network of interconnected lanes/roads, prioritizing efficient routing for emergency vehicles, and through simulations, demonstrates significant reductions in emergency vehicle travel times of up to 50% for the centralized scheme and up to 30% for the decentralized scheme without causing congestion in other lanes. This paper introduces EMV light, a decentralized reinforcement learning framework that simultaneously optimizes dynamic routing and traffic signal control for emergency vehicles in real time, significantly reducing travel times for both emergency vehicles and non-emergency vehicles while outperforming traditional transportation engineering techniques and existing reinforcement learning-based signal control methods in experiments [26].

In this paper, a smart traffic light controller with emergency vehicle detection is designed using Verilog HDL and implemented on Altera DE2-115 FPGA. FPGA is superior to microcontroller in terms of input and output port count, improved performance, high speed, and design flexibility [22]. This designed system detects a single emergency vehicle at a four-way traffic light intersection and controls the traffic light conditions for smooth traffic flow. The design's functionality was verified using QuestaSim's timing simulation diagram and an Altera DE2-115. The smart traffic light controller for emergency vehicle detection will priorities the emergency vehicle going through the traffic light. If the emergency vehicle is given precedence, the outcome will be drastically different. More lives can be saved, and people's safety can be guaranteed. Next, the original role of a traffic lights is to ensure the smooth functioning of the road flow and the safety of the road user. This project improves present operations while also ensuring the safety of road users.

2. METHOD

The proposed smart traffic light controller for emergency vehicle detection can identify the presence of a single emergency vehicle as well as the traffic congestion on a four-way traffic light intersection. Figure 1 depicts the layout of the four-way traffic light intersection installed with infrared (IR) and inputs radio frequency identification (RFID) readers. The location of traffic lights, IR sensors, RFID readers as well as the distance between them shown in the layout. Road intersection with four lanes is labelled as North, East, South, and West. This project employs four traffic lights, four RFID readers and eight IR sensors. The red square box represents the traffic light, the yellow square box represents the IR sensor, and the green square box represents the RFID reader. RFID readers can identify the presence of an emergency vehicle within a 100 meter radius, while the number of active IR sensors detects the traffic density. Once the RFID reader detects the emergency vehicle's unique RFID tag, the green light for the detected lane will be turned on for at least 50 seconds to allow emergency vehicle to pass by. While for the IR sensor, the number of activated sensors on each lane will determine the timing duration for the green light for that lane as tabulated in Table 1.

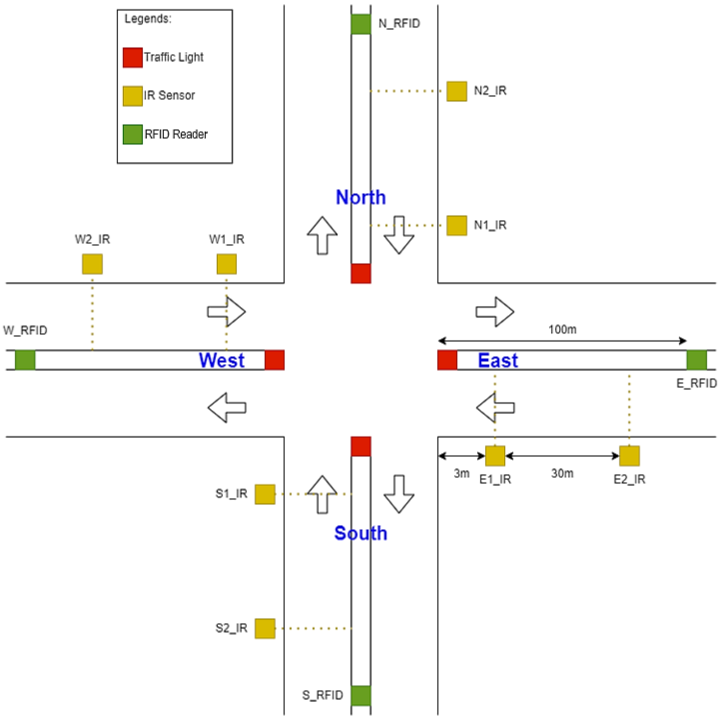

Figure 1. Four-way traffic light intersection with sensors

Table 1. Green light timing duration based on the number of activated IR sensors

No. of activated IR sensors	Timing duration for green light (second)	Traffic density
0	0	Zero density
1	15	Low density
2	30	High density

The top level with internal architecture of smart traffic light controller for emergency vehicle detection is shown in Figure 2. The top level represents the block diagram of the traffic light controller system with RFID readers and IR sensors used as inputs while light-emitting diodes (LEDs) are used as outputs. Each lane is equipped with one RFID reader, two IR sensors and three LEDs: green, yellow, and red. Another important inputs included in the smart traffic light controller is clock input which used to synchronised the controller operations and reset input which used to reset the operation to initial state. A clock frequency of 50 MHz from the Altera DE2-115 FPGA is used in this design as a master clock input. The 50 MHz master clock is reduced to 1 Hz by the clock division sub-module. The generated 1 Hz clock is used by other sub-modules such as counter and finite state machine (FSM) operation. The 7-bit counter sub-module counts up at every rising edge of clock and provides the counted output value to the FSM operation sub-module. The FSM operation sub-module also will incorporate the RFID and IR inputs. This project exclusively utilizes RFID and IR technology concepts. In contrast, this prototype replaces RFID and IR sensors with FPGA board slide switches. The FSM operation will conduct the operation and generate output conditions based on the input received. The output created by the FSM operation will be sent to the FPGA board's LEDs.

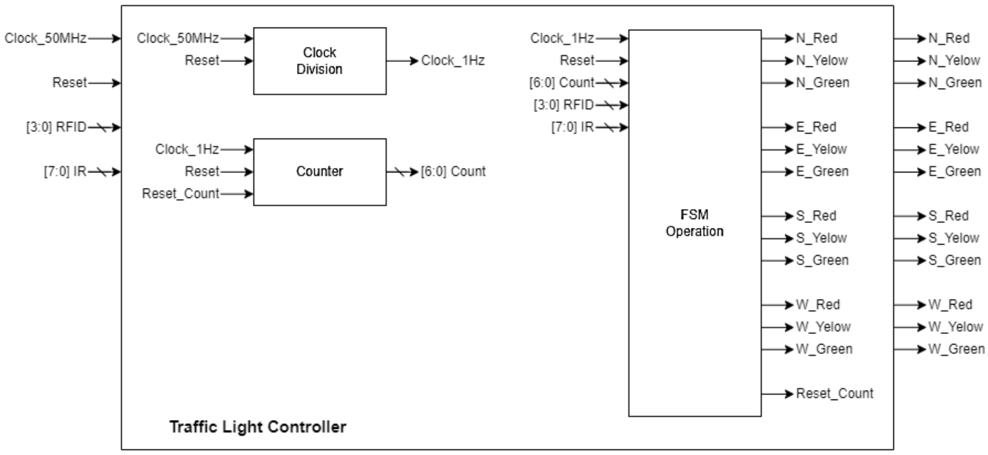

Figure 2. Top level with internal architecture of smart traffic light controller for emergency vehicle detection

Table 2 presents corresponding IR and RFID bits segmentation according to lane (North, East, South, and West). Eight IR inputs represented by 8-bits binary input while four RFID inputs represented by 4-bits binary number. Each bit of a 4-bit RFID represents an individual emergency vehicle on its lane. RFID bit 0 corresponds to the North Lane, RFID bit 1 corresponds to the East Lane, RFID bit 2 corresponds to the South Lane, and RFID bit 3 corresponds to the West Lane. While each 2-bits of an 8-bits IR input were assigned to each four-lane segment to describe the road's density, IR bits 0 and 1 correspond to North Lane, IR bits 2 and 3 correspond to East Lane, IR bits 4 and 5 correspond to South Lane, and IR bits 6 and 7 correspond to West Lane.

Table 2. IR and RFID bits segmentation according to lane

Input signals	Bits segmentation (by Lane)							
	West Lane		South Lane		East Lane		North Lane	
8-bits IR	IR [7]	IR [6]	IR [5]	IR [4]	IR [3]	IR [2]	IR [1]	IR [0]
4-bits RFID	RFID [3]		RFID [2]		RFID [1]		RFID [0]	

Figure 3 depicts the project's flowchart. This flowchart shows the project's operating flow, which begins with detecting the RFID tag (emergency vehicle installed with RFID tag) at all lanes, beginning with North, followed by East, South, and finally West. The presence of an emergency vehicle will be detected by an RFID reader. If an RFID reader detected emergency vehicle at one lane, the traffic light for the detected lane will turn green for 50 seconds and the other lanes will turn red for the same period. If no emergency vehicle is present, the traffic light controller will control the traffic light condition based on the traffic density (detected using IR sensors). Each lane has installed with two IR sensors. As indicated in Table 1, the number of activated IR sensors on each lane indicate the traffic density and are used to determine the timing duration of the green light for the lane. The duration of the green light on a high traffic density is 30 seconds, while on a low traffic density it is 15 seconds. If the North traffic light lane has a high traffic density, the North traffic light lane will turn green for 30 seconds and the other lanes will turn red for the same length of time. If the North traffic light lane has a low traffic density, the North traffic light lane will turn green for 15 seconds and the other lanes will turn red for the same length of time. Then, if the North lane is empty, the IR sensors will examine the following lane. The checking order start from North, then East, then South, and finally West. Upon completion of each action, the system will continuously loop back to the RFID reader detection, indicating that it is continuously monitor the presence of emergency vehicle.

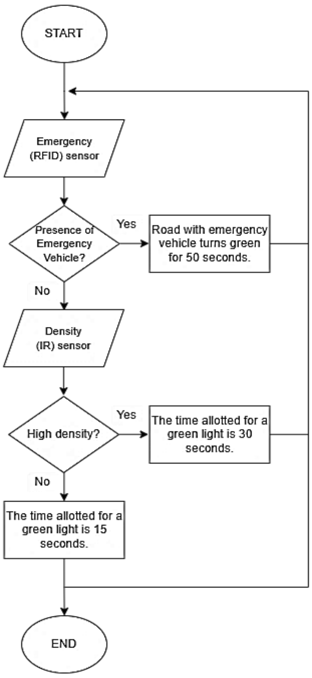

Figure 3. Flowchart of smart traffic light controller for emergency vehicle detection

FSMs are sequential circuits used in a wide range of digital systems to manage system behavior and data flow routes [27], [28]. The FSM employed in designing the FSM operation sub-module is responsible for determining and storing the operation states. Figure 4 illustrates the FSM for the smart traffic light controller. The operation starts in the check RFID state. If an emergency vehicle (EV) is detected (RFID≠0000), the lane with the EV is turned green for at least 50 seconds. Once the 50 seconds have elapsed, and if the EV is no longer detected, the light transitions to yellow for 5 seconds before returning to the check RFID state. If no EV is detected (RFID=0000), the system moves to the check IR state. Here, traffic is evaluated sequentially for the North (N), East (E), South (S), and West (W) lanes. Depending on traffic density, the green light is activated for either 30 seconds (for low traffic density) or 15 seconds (for high traffic density). After the designated green light duration, the lane turns yellow for 5 seconds before reverting to the check RFID state. While a lane is green, the RFID status is continuously monitored. If an EV is detected in any lane during this period, the current green lane will switch to yellow for 5 seconds and return to the check RFID state. The system then immediately activates the green light for the lane with the detected EV, ensuring that emergency vehicles always receive priority.

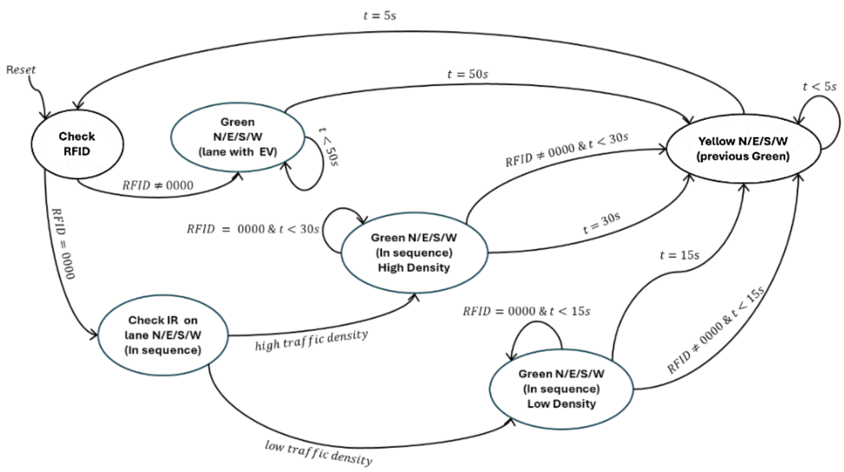

Figure 4. FSM of smart traffic light controller for emergency vehicle detection

As depicted in Figure 5, the hardware of the smart traffic light controller for emergency vehicle detection is implemented utilizing an Altera DE2-115 board. On a breadboard, four traffic lights modules are attached to the FPGA board to simulate the traffic light controller at a four-way traffic light intersection, namely North, East, West, and South. The function of the push button is to reset the operation. Switch 0 to switch 7 on the board are used to represent eight IR sensor inputs, whereas switch 14 to switch 17 are used to represent the four RFID inputs. One push button is used as reset input and all lights (leds) are connected via 40 pin GPIO expansion header.

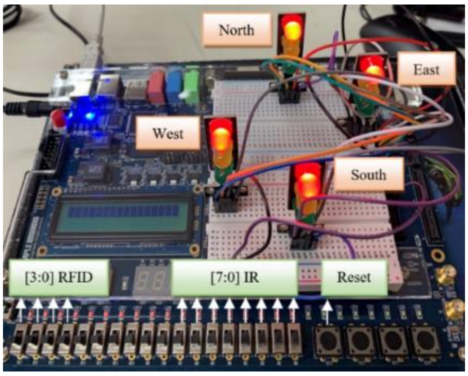

Figure 5. Hardware implementation of smart traffic light controller for emergency vehicle detection

3. RESULTS AND DISCUSSION

3.1. Simulation result

The code for the smart traffic light controller, designed for detecting emergency vehicles, has been synthesized using Quartus Prime 21.1. In Figure 6, you can see the RTL schematic diagram, which illustrates the connections of inputs, outputs, and wires linking the clock division, counter, and FSM operation sub-modules.

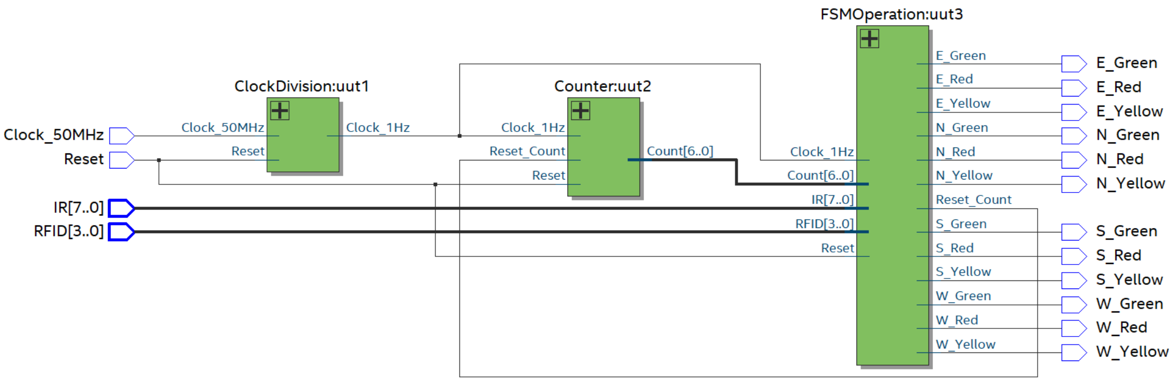

Figure 6. RTL schematics diagram of smart traffic light controller for emergency vehicle detection

The simulation was carried out using Questa Intel FPGA Starter Edition. Figures 7 to 10 demonstrate the simulation outcomes for various sensor activation circumstances. The activation time for the yellow light is always 5 seconds, however the activation times for the green and red lights vary based on the traffic density. The waveform when no RFID tag is detected and the IR sensors are active is depicted in Figures 7 and 8.

Figure 7 demonstrates that high traffic density (IR=11 11 11 11) on all lanes without the presence of an emergency vehicle. The North Lane turns green for 30 seconds while the other lanes turn red, and then the North green turns yellow for 5 seconds while the other lanes remain red. The East Lane then goes green for 30 seconds, while the North Lane yellow turns red and the remaining lanes remain red. Then, East green turns yellow for 5 seconds while the other lanes remain red. The sequence continues for South Lane, and lastly for West Lane. The waveform thereby confirming the green light permissible time for high traffic density. The sequence of active green light for this traffic light is North > East > South > West, with turn for a lane having no or zero traffic density will be skipped.

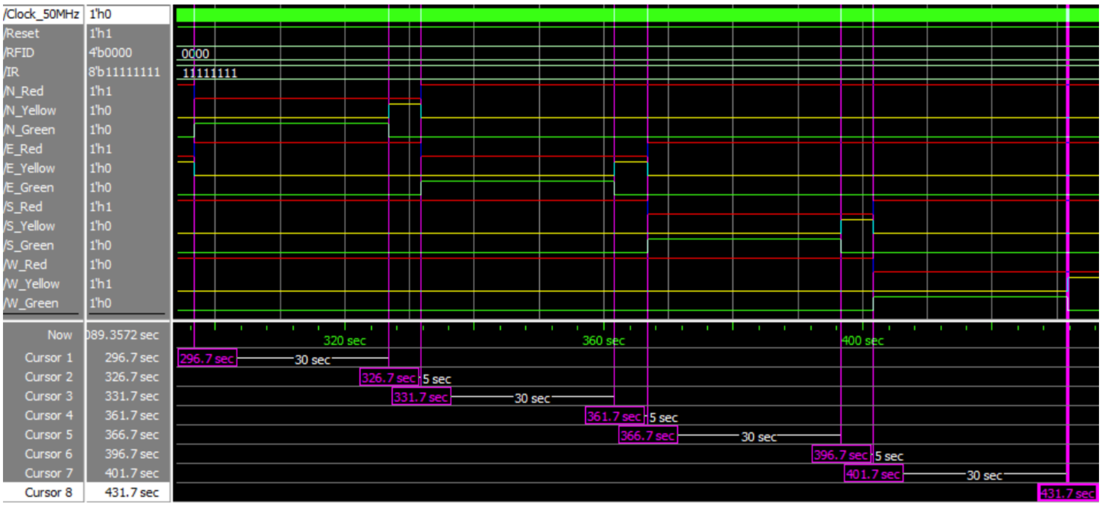

Figure 7. High traffic density on all lanes without an emergency vehicle

Figure 8 demonstrates that random traffic density (IR=01 01 00 11) on all lanes without the presence of an emergency vehicle. IR=01010011, which indicates that the North Lane has a high traffic density, the East Lane has no vehicle, and the West and South Lane have a low traffic density. The North Lane should turns green for 30 seconds due to high traffic density while the other lanes turn red. Suddenly, at time 165 second, IR condition changes to 11010011 and obviously the condition of the lights will change based on the new IR condition. The sequence of active green will still maintain where North Lane maintain green until reach 30 seconds, and then the North Lane turns yellow for 5 seconds while the other lanes remain red. Next, East Lane should take it turn, but there is no vehicle (zero density) detected on East Lane. Therefore, it will proceed to the next lane, the South Lane. The South Lane then goes green for 15 seconds due to low traffic density while the other lanes turn red. Then the South Lane turns yellow for 5 seconds red. At this time, the condition of IR is still same, the North Lane take turn where the North Lane turns green. The North green light should turn on for 30 seconds due to the high traffic density. However, at time 255 second, the RFID status change to 0010 which indicate that there is an emergency vehicle at South Lane. The present of the emergency vehicle automatically change the North Lane to yellow for 5 seconds although the green light not completely turn on for 30 seconds. This shows that an emergency vehicle is always given priority.

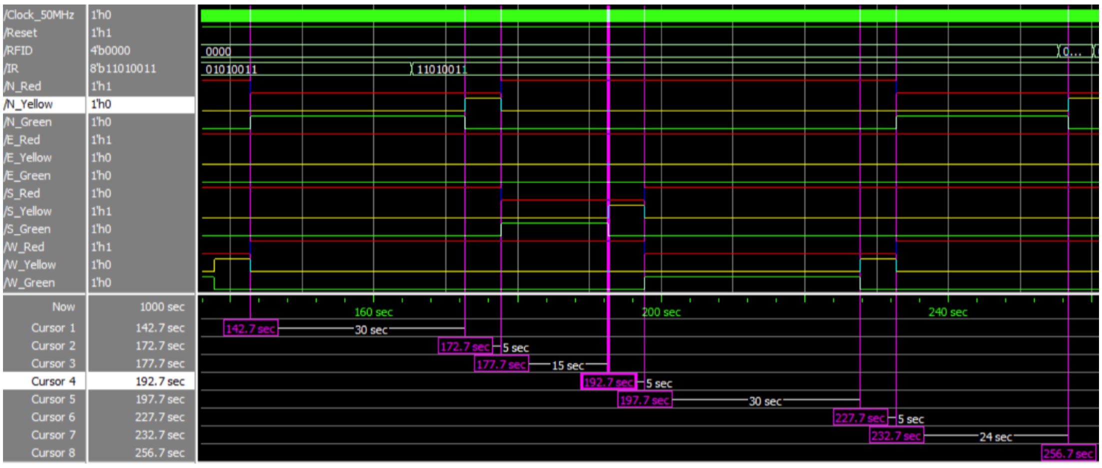

Figure 8. Random traffic density on all lanes without an emergency vehicle

The waveform when emergency vehicle is detected (RFID≠0000) is depicted in Figures 9 and 10. The permissible time for the green light on a road with the presence of an emergency vehicle is 50 seconds. Figure 9 demonstrates that high traffic density (IR=11 11 11 11) on all lanes with the presence of an emergency vehicle at West Lane (RFID=1000). Before the detection of the emergency vehicle, the North Lane is on green condition. After 20 seconds turn green, emergency vehicle detected on West Lane and West Lane automatically turns yellow for 5 seconds. Then, West Lane becomes green for 50 seconds while the other lanes turn red to allow emergency vehicle to pass by the junction. After that, if the emergency vehicle is not detected anymore (indicate that the emergency vehicle successfully passed by the junction), the traffic condition will follow normal traffic sequence (North > East > South > West). Then, North Lane take turns which turn green for 30 seconds due the high traffic density and continue normal traffic light operations.

Figure 10 demonstrates a random traffic density (IR=11 01 00 11) on all lanes with the presence of an emergency vehicle at East Lane (RFID=0010). The IR condition indicates that the West and North Lane have a high traffic density, the East Lane has a zero traffic density, and the South Lane has low traffic density. Before the detection of the emergency vehicle, the traffic light operates in a normal condition with the green light timing is controlled by the traffic density. At time 269 seconds, an emergency vehicle detected on East Lane which automatically interrupt the traffic light operation. North Lane which was just turn green for 4 seconds at that time, automatically turn yellow for 5 seconds. Then, the East Lane turns green for 50 seconds (remaining lanes turn to red) to allow the emergency vehicle to pass the junction.

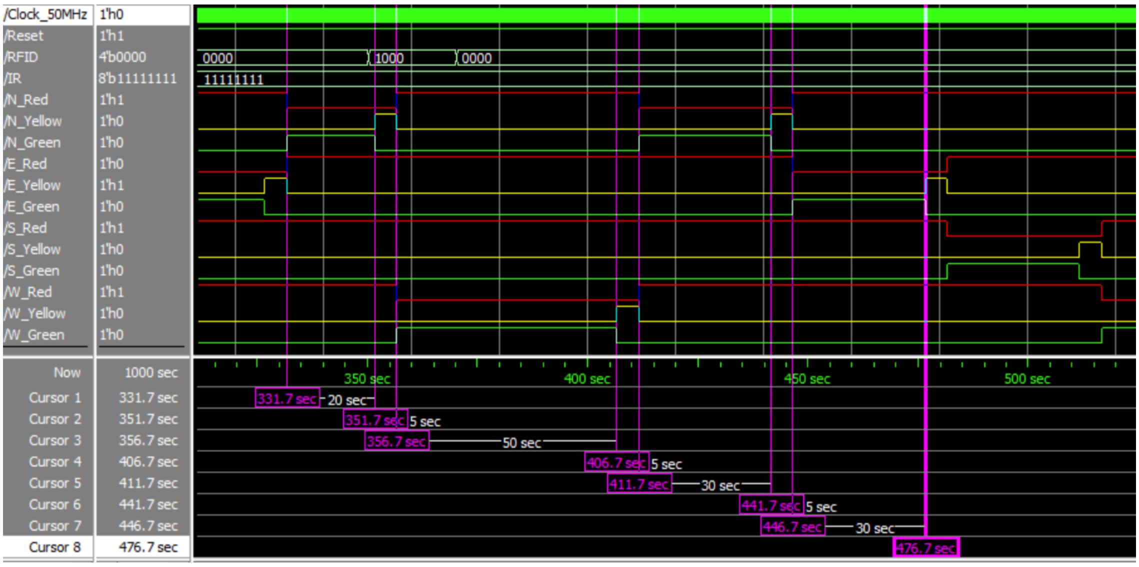

Figure 9. High traffic density on all lanes with an emergency vehicle

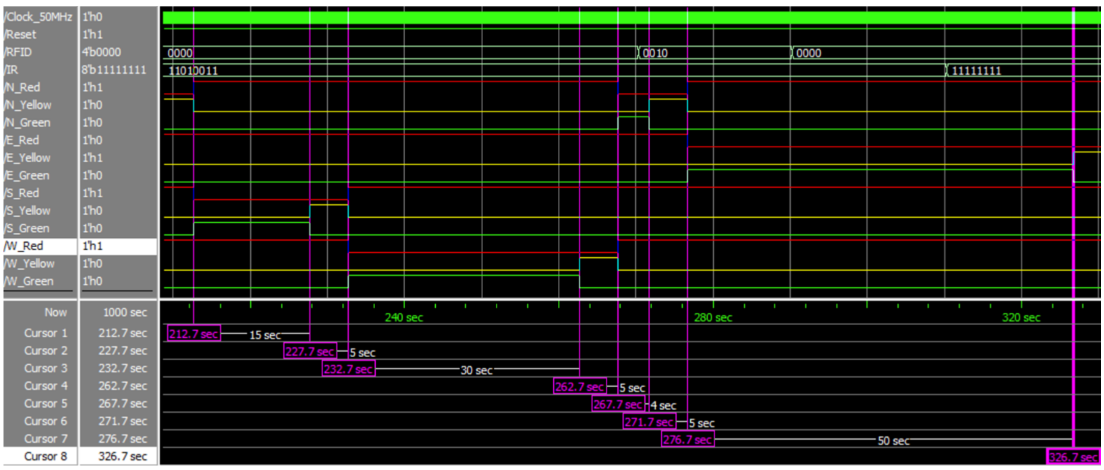

Figure 10. Random traffic density on all lanes with an emergency vehicle

3.2. Hardware (FPGA) implementation result

Figures 11 and 12 show the traffic light conditions (prototyping using Altera DE2-115) of the smart traffic light controller for different input conditions. Figures 11(a) to (d) demonstrate low traffic density on all lanes (IR=01010101) without the presence of an emergency vehicle. The North Lane turns green for 15 seconds while the other lanes turn red as in Figure 11(a), and then the North Lane turns yellow for 5 seconds while the other lanes remain red as in Figure 11(b). The East Lane then goes green for 15 seconds, while the North Lane turns red and the remaining lanes remain red as in Figure 11(c). Then, East Lane turns yellow for 5 seconds while the other lanes remain red as in Figure 11(d). Next, the South Lane then goes green for 15 seconds, while the East Lane turns red and the remaining lanes remain red.

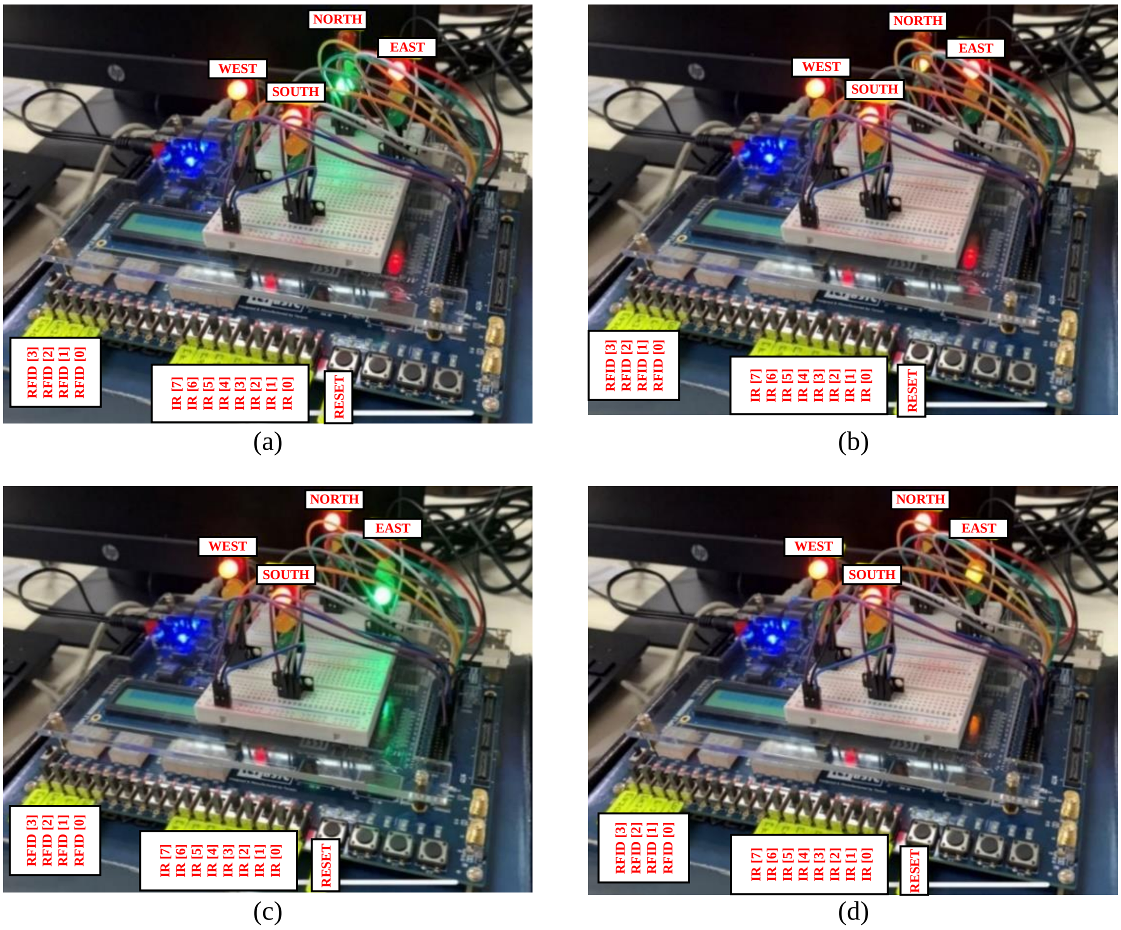

Figure 11. Traffic light condition of prototype for IR=01010101 and RFID=0000; (a) North Lane green, others lane red, (b) North Lane yellow, others lane red, (c) East Lane green, others lane red, and (d) East Lane yellow, others lane red

Figure 12 demonstrates the condition for low traffic density (IR=01 00 00 00) with the presence of an emergency vehicle at East Lane (RFID=0010). As a result, the current lane, which is the South Lane, completes its green light counting and becomes yellow for 5 seconds, as seen in Figure 12(a). The South Lane is subsequently followed by the West Lane, however there is an emergency vehicle in the East Lane, thus the East Lane turns green for 50 seconds while the other lanes turn red as in Figure 12(b), and then the East green turns yellow for 5 seconds while the other lanes remain red as in Figure 12(c). Figures 12(a)-(d) demonstrate that now the North, East, and South Lanes are now devoid of any vehicles, whereas only the West Lane has vehicles present, as the IR is now 01000000. There is no RFID detection as in Figures 12(c) and (d) because the emergency vehicle has passed, so that after the East Lane turns yellow, the West Lane will turn green.

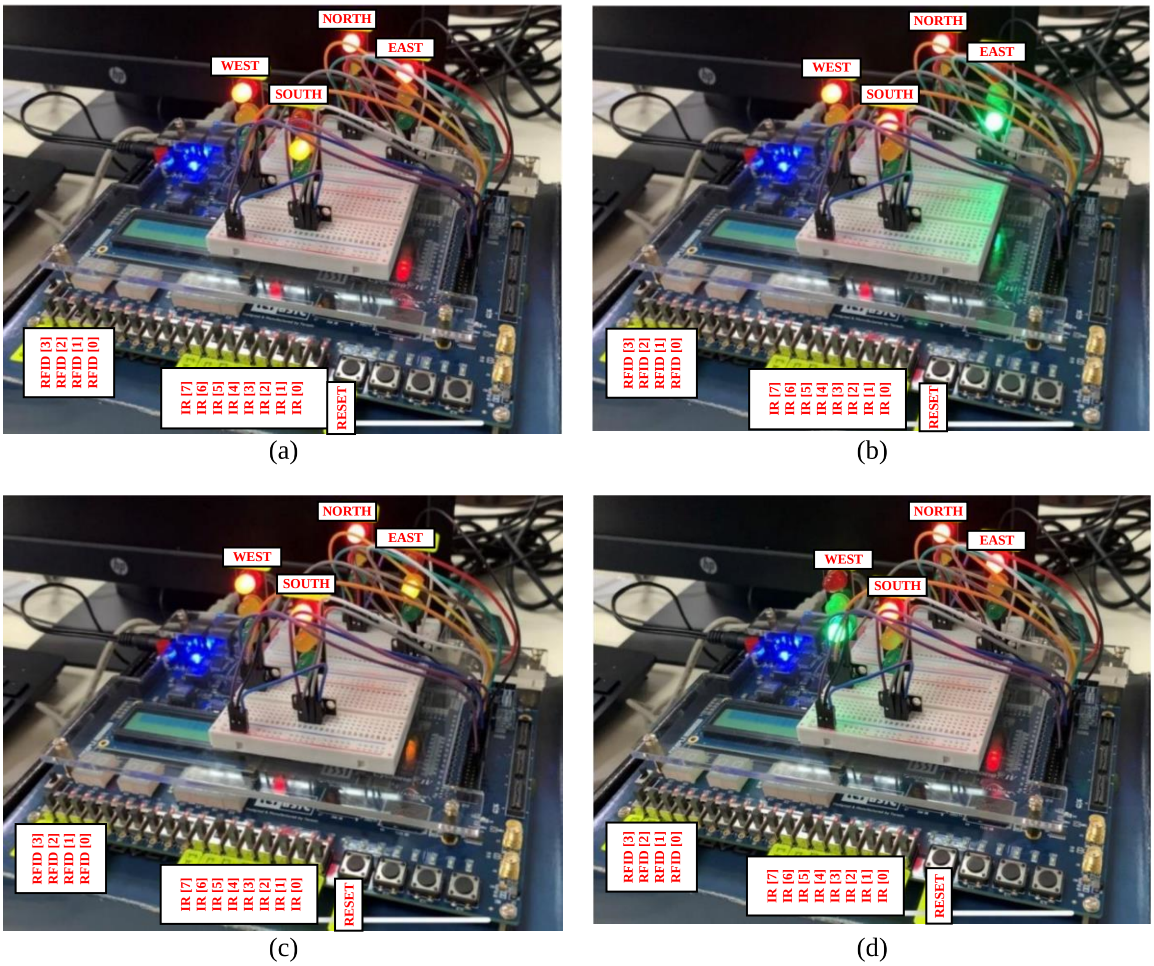

Figure 12. Traffic light condition of prototype for IR=01000000; (a) RFID=0010-South Lane yellow, others lane red, (b) RFID=0010-East Lane green, others lane red, (c) RFID=0000-East Lane yellow, others lane red, and (d) RFID=0000-West Lane green, others lane red

4. CONCLUSION

In conclusion, the Verilog HDL-designed and FPGA-implemented smart traffic light controller for emergency vehicle detection's objective of identifying the presence of emergency vehicles and traffic congestion at certain intersections has been met. The project guarantees that emergency vehicles pass smoothly by constantly checking for the presence of an emergency vehicle and prioritising the road with the emergency vehicle. The design's functionality was analyzed with the Questa timing simulation diagram and the Altera DE2-115 board and functioning as intended. For future work, it is suggested to incorporate true RFID and IR sensors as opposed to using them as switches. Therefore, we can confirm that RFID and IR technology can be implemented on FPGA. It is then suggested that more IR sensors be added to improve the effectiveness of monitoring the traffic density. Another improvement is to make it possible to simultaneously detect the presence of many emergency vehicles.

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