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Design and implementation of a real-time demonstration setup for dynamic highway tunnel lighting control research studies

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Abstract

This study presents the design and implementation of a computer-based real-time demonstration setup for dynamic highway tunnel lighting control research studies. The energy-efficient and controllable lighting systems stand out worldwide because of energy efficiency objectives and carbon footprint reduction goals of the countries. An LED (Light Emitting Diode) armature-based highway lighting systems are frequently utilized in recent years due to lighting efficiency, energy efficiency, long life, environmentally and cost-friendly structure of the LEDs as well as zero ultraviolet emissions of them. In this study, the LED-based dynamic tunnel lighting control approach has been implemented through the proposed demonstration setup which is a typical real-time software-controlled hardware. The parts of the proposed demonstration setup have been introduced and detailed to help with some upgrade studies in the future. The demonstration setup has been tested in some case studies, then the obtained results have been discussed and introduced. In the future, the proposed system can be upgraded and utilized for advanced control studies thanks to its computer-based and simulation environment connection capability.

1. Introduction

Turkey is a predominantly mountainous country. When looking at the geographic structure of Turkey, it is seen that Turkey is surrounded on three sides by the seas, which are Black Sea, Mediterranean Sea and Aegean Sea. The Mediterranean is in the south, the Aegean is in the west, and the Black Sea is in the north of Turkey. It is also known that mountains form parallel to the sea along the Black Sea and Mediterranean coastlines, and perpendicular to the sea on the Aegean Sea coasts. In addition, there are volcanic mountain formations and mountain formations rising by breaking in the regions in the east of Turkey. These geological features of Turkey create a great obstacle on the roads built for transportation.

Tunnel constructions for highway routes are being more and more important in the world as well as Turkey. Transportation can be accelerated, and optimum protection can be procured for the environment and the landscape through the highway tunnels. Lengths and capacities of the tunnels are increased tremendously day by day, thanks to the emerging tunnel technologies. In long tunnels lighting is an essential issue of the tunnel to provide safely and comfortably driving to the drivers. Emerging carbon economy and energy efficiency targets are becoming a worldwide trend. Therefore, LED (Light Emitting Diode) armature-based tunnel lighting systems have increased progressively in the tunnels due to lighting efficiency, energy efficiency, long life, environmentally and cost friendly structure of the LEDs as well as zero ultraviolet emissions of LEDs [1-4]. However, appropriate lighting is important for drivers' visual perceptions to avoid the black hole effect which reduces visual perception of the drivers. It has been determined that traffic accidents in tunnels frequently experience at the entrances and exits of the tunnels [5-6]. Therefore, the tunnel lighting must always procure maintained visual perceptions for drivers, both day and night, during sudden lighting level changing by their entering and exiting the tunnel. Also, optimum and dynamic lighting control has an important role in energy consumption of the tunnel lighting.

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Traditional tunnel lighting systems, which are independent of the lighting situation outside the tunnel, are carried out by sodium vapor lamps. These lamps have high power consumption, and their voltage level and light intensity cannot be changed. LED lamps, on the other hand, have both low power consumption and light intensities that can be adjusted by changing the operating voltage [7-8]. Therefore, the LED lamps allow to adjust the illumination levels at the entrance and exit of the tunnels.

The tunnel zones, tunnel lighting criteria and standards have been defined and introduced by [9-10]. Following figure presents the zones in the tunnel and lighting designs of them to avoid encountering the black-hole effect and or bright hole effect and help drivers adapt to the lighting environment in the tunnel when drivers enter the tunnel.

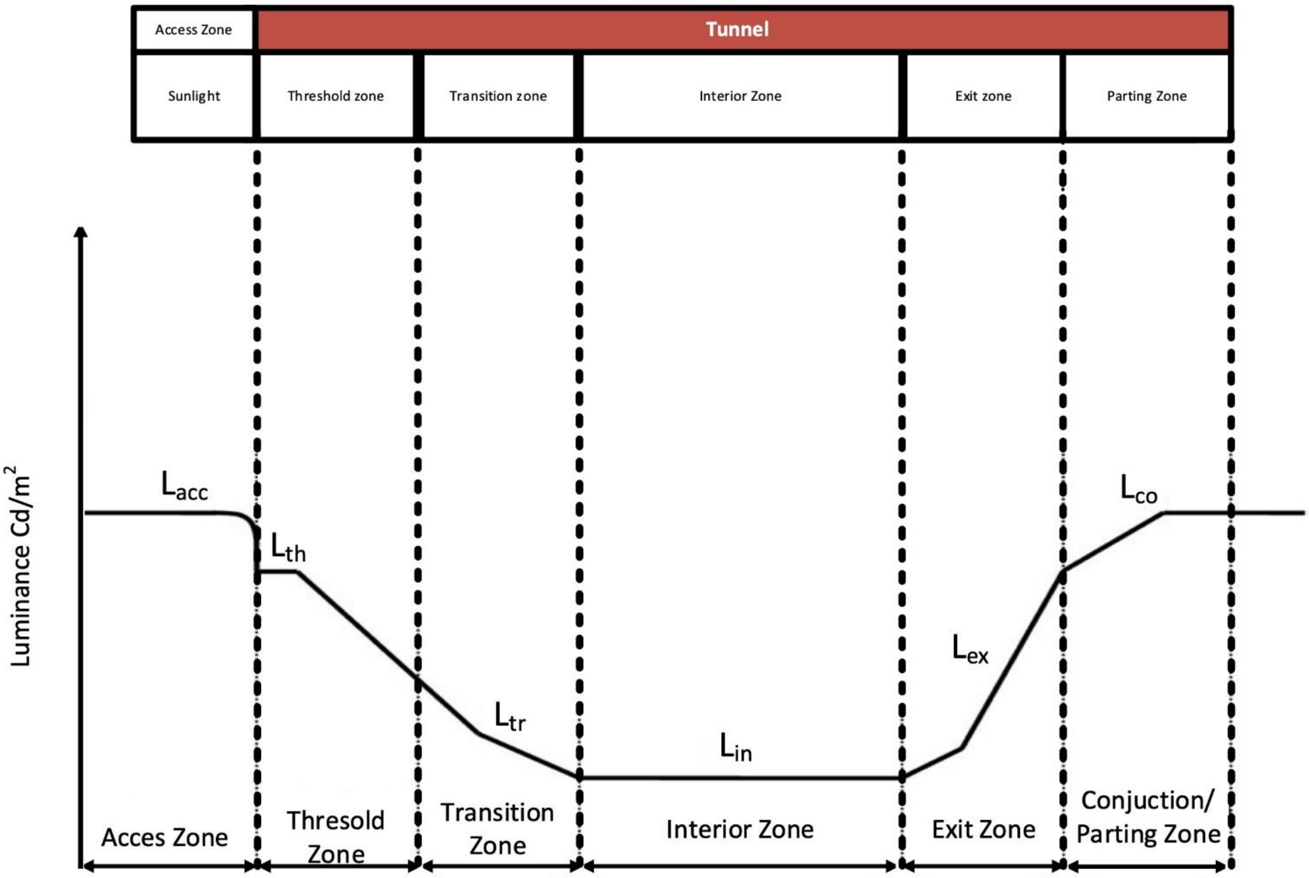

Figure 1. Zones in the tunnel and lighting designs of them. Adapted from [9-10]

There are some of the optimal tunnel lighting and lighting control systems which are proposed by both the literature and tunnel lighting companies. For example, Schréder company proposes intelligent tunnel lighting solutions which help the driver's eyes to adjust easily and quickly [11]. In similarly, the Thorn Lighting company offers tunnel lighting solutions which have fully integrated control systems to provide adaptive lighting system as to level of light outside the tunnel, time of day, speed and density of traffic [12]. An automatic controlled highway tunnel lighting system has been proposed by [13] to meet lighting requirements and to provide energy efficiency. Their proposed automated stepless dimming control strategy provides energy saving 80% more than high pressure sodium lamps, 35 % more than classical rating dimming LED lamps and 20% more than traditional four steps-controlled LED lamps. Zeng et al., [8] have been designed a fuzzy based control algorithm for LED lighted tunnels by utilizing traffic flow and the outside illumination level as the intelligent lighting control parameters. Their proposed fuzzy logic-based LED lighting control system has been utilized in a real highway tunnel and it has been calculated that 87 % decrease in energy consumption for a ten-month period. Xu et al., [14] have been proposed an LED lighting control structure for highway tunnels in order to provide soft and reliable dimming of the LEDs and avoid adaptability problems of the drivers due to brightness changes thanks to adapting the digital addressable lighting interface. They have been utilized step-down power electronics devices to drive the LEDs, and control of the LED driver has been performed by using luminance level sensors and vehicle detectors in the control system. Wang et al., [15] have been asserted a dynamic dimming control system for LED lighting of the tunnels through a demonstration project. They have been reported energy saving the advantages of dynamic dimming-controlled LED based tunnel lighting over the high voltage sodium lamp and constant luminance LED lighting. Qin et al., [16] have been designed an intelligent luminance control method for tunnel lighting by considering the traffic flow in the tunnel. Their proposed system has two operational strategies which called as day and night operations. In the day operation, the luminance of the tunnel's zones is controlled as to the luminance of the tunnel's entrance and exit. In the night operation, the luminance is increased when the vehicle is entering the tunnel, it decreased when the vehicle is exiting the tunnel through the proposed strategy.

In this study, an LED (Light Emitting Diode) based dynamic tunnel lighting approach has been designed and implemented through devising real time software-controlled hardware by considering the above-mentioned literature. Although utilizing of LED lamps provides incontrovertible energy efficiency due to their low energy consumption [7,8,13], this study focuses on to increase safety driving process of the drivers in a highway tunnel by the proposed LED lighting control system. Thus, it is aimed to provide a dynamic LED dimming mechanism which increases the visual adaptation of the drivers by controlling the light level of the transition areas in the tunnel when the light level in the outdoor environment changes. In order to provide a demonstration and to make a design and development platform for control of LED dimming-based tunnel lighting systems, a real-time simulation and PC controlled hardware implementation system have been devised on an emulated tunnel prototype. The remainder of the paper is organized as follows: Section 2 focuses on material and method of the study; Section 3 presents the results and Section 4 gives the conclusion.

2. Material and Method

The emulated prototype tunnel dimensions have been determined by scaling the entrance, exit, interior and transition regions of the tunnels, considering the above-mentioned literature on tunnel lighting systems. The sensor circuits, which sense the brightness of input and output of the tunnel, and the LED driver circuits and have been designed and data connection with them to the development card have been performed. Arduino Mega 2560 has been utilized as the development card. Since the brightness of the LEDs is directly proportional to their voltage levels, the brightness control has been performed by DC/DC step-down converter and it has been controlled via designed Proportional-Integral (PI) controller. In order to drive the LEDs, the Pulse Width Modulation (PWM) signal which is adjusted by the controller output has been used. The real-time operation of the system has been carried out in MATLAB/Simulink simulation environment. Therefore, after the simulation model has been tuned up and the errors have been fixed the simulation model has been transferred to the Arduino development card through PC communication.

The operation logic of the system can be described simply by following equation:

$$O(t) = \left[K_p e(t) + K_i \int_0^t e(t)dt\right] x L_c \tag{1}$$

where,

O(t): Operation signal which is sent to the LED driver.
K_p: Proportional coefficient of the PI controller.
K_i: Integral coefficient of the PI controller.
e(t): The difference between reference lighting level and measured lighting level.
L_c: Lighting coefficient which provide different lighting in the zones of tunnel.

In this study, the controller parameters Kp and Ki are tuned through MATLAB Simulink Control System Toolbox. The Kp and Ki are used as 0.5 and 0.005 respectively. The saturation blocks which are used in the output of the PI controller limits the data between 0 and 255 due to PWM blocks of the Arduino operate in 8-bit data.

Following subchapters introduce the parts of the proposed system and devised platform, and their designs.

2.1. Real-time simulation of the system in the MATLAB/Simulink environment

Fig. 2 shows the real-time simulation blocks of the system in the MATLAB/Simulink environment. External (out of the tunnel) illumination data have been read and transferred to the control unit through the light sensors located in the entrance and exterior zones of the tunnel structure. These data have been utilized in compliance with the above-mentioned tunnel lighting essentials. The DC/DC step-down converters are located at the outputs of the control card both acts as a driver for adjusting the light intensity and transfers the necessary information to the feedback circuit in order to control the desired light level. In this system, day and night transition and its application has been performed via the algorithm which changes the operational logic of the system in day and night conditions. Lighting levels outside the tunnel are read by the sensor and switch to night mode when the illumination level decreased to the night level. So, the system continues operating in a way that can be described as the opposite of the day operation.

2.2. Light sensor circuit

The light sensor circuit is shown in Fig. 3. Its structure is like a voltage divider with LDR. The illuminance levels at the entrance and exits of the tunnel are measured through this light sensor circuit.

2.3. DC/DC step-down converter circuit

A DC/DC buck converter, in other words DC/DC step-down converter, is a power electronic device which reduces voltage from its input (supply) to its output (load).

Fig. 4 shows the circuit of the traditional DC/DC step-down converter. The DC/DC step-down converter provides the desired voltage level by reducing the mean value of the input voltage via chopping. The input voltage of the converter is chopped through the pulse width modulation (PWM) signals, which are provided by the PI controller output in this study.

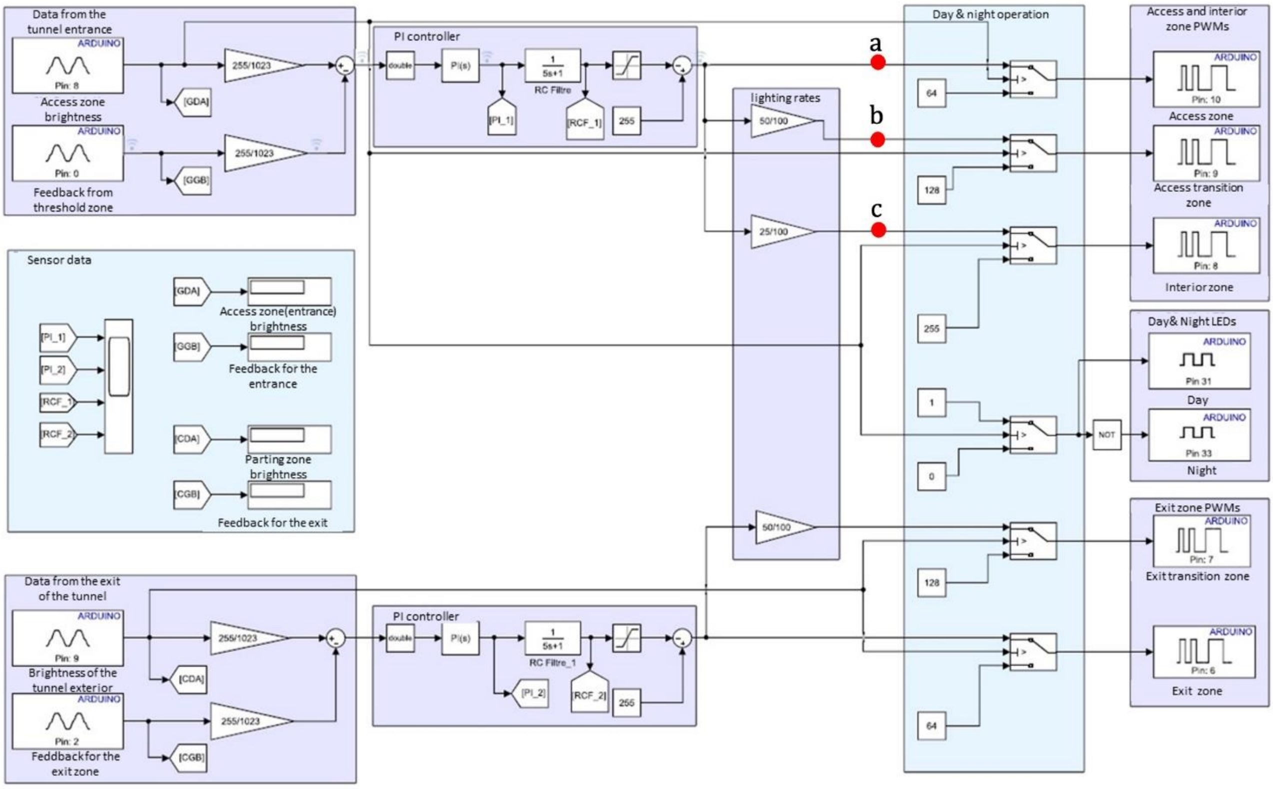

Figure 2. Zones in the tunnel and lighting designs of them

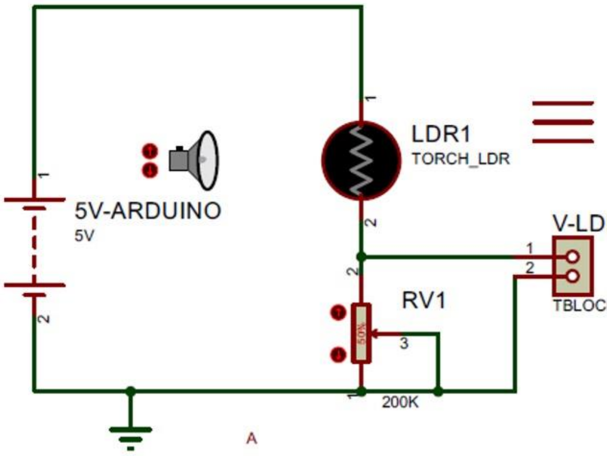

Figure 3. Light sensor circuit

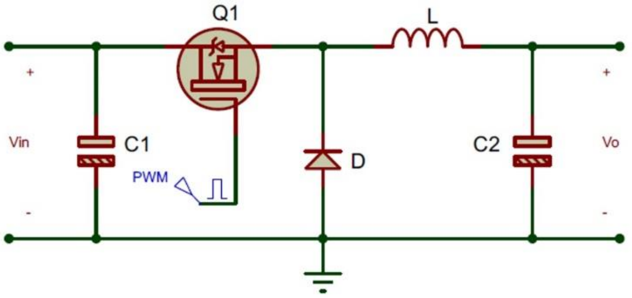

Figure 4. Traditional DC/DC step-down converter circuit diagram

An average voltage is obtained from the output of the DC/DC step-down converter as to the on or off state of the Q1 switch which is given in Fig. 4. As it can be seen in Eq. (2), the average voltage depends on the duty cycle (D) which determine the on-off state of the Q1 switch.

$$D = \frac{Vo}{Vin} \text{ and } 0 \leq D \leq 1 \tag{2}$$

In Eq. (2), Vo is the output voltage of the converter and Vin is the input voltage of the converter. The sum of the on and off times of the Q1 switch is called the period which is denoted by Ts. It is presented in Fig. 5.

The graph in Fig. 5 shows the voltage between the terminals of the Q1 switch. Accordingly, the switch Q1 is open during the t_{on} time, and the switch is closed during the time indicated by t_{off}. So, the mean value of the output voltage will be changed by duty cycle (D) as it presented in Eq. (3).

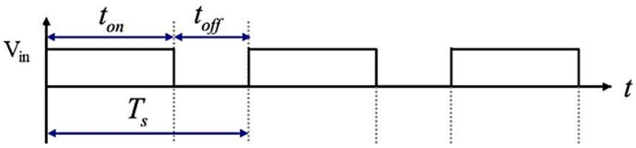

Figure 5. Chopping the input voltage as to duty cycle which determine on and off time of the Q1 switch.

$$Vo = D.Vin \tag{3}$$

The role of the duty cycle and PWM signals in this proposed system can be explained as follows. When the duty cycle is changed by the controller, the PWM signals change, then the voltage of the LEDs changes.

The following figure shows that the response of the controller and PWM signals when the error (the brightness difference between inside and outside of the tunnel) is changed.

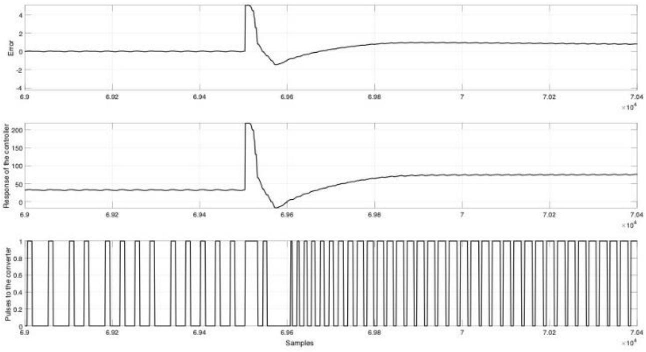

Figure 6. The response of the controller and PWM signals when the error is changed.

Fig. 7 shows the DC/DC step-down converter circuits used in this study. Due to its structure, this circuit allows the voltage in the range of 5 V to 35 V given to its input to be adjusted between 0 V and input voltage according to the duty cycle sent by the control unit. Module LEDs operating with 12 V are used in the circuit in the tunnel lighting system that was applied. For this reason, LED lighting has been controlled to give an output between 0 V and 12 V by applying 12 V voltage to the DC/DC step-down converter input.

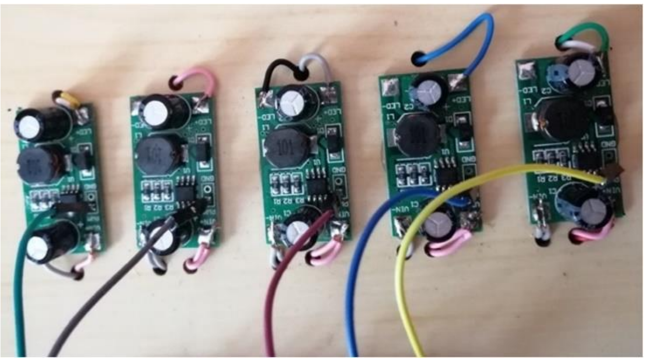

Figure 7. DC/DC step-down converter circuits used in this study.

2.4. The feedback circuit

The feedback circuit is given in Fig. 8. This compares illumination of the entrance and exit transition zones with the exteriors of the tunnel. It is basically a voltage divider made with a resistor and a potentiometer. In addition, a voltage follower circuit with LM358 OPAMP is designed and in order to provide the system more stable and to create a high impedance at the output of the voltage divider. This circuit is placed to end of the voltage divider. The voltage follower circuit is presented in Fig. 8.

In Fig. 9, the printed circuit board (PCB) layout diagram and 3D model of the feedback circuit which includes the voltage divider and voltage follower.

2.5. PWM driver and signal inversion circuit

Fig. 10 shows the PWM driver, and the signal inversion circuit used in this study. This circuit basically consists of five transistor switch circuits. The signal inversion circuit creates a 180° phase difference in the signal which comes from Arduino MEGA 2560 control card. The boughten ready to use DC/DC step-down converter, which is shown in Fig. 7, operates inversely proportional to the duty cycle because of its production nature. So, this signal inversion has been utilized to ensure operation of the DC/DC converter as it is introduced in Eq. (2). Fig. 11 shows printed circuit board (PCB) layout diagram and 3D model of the designed and implemented signal inversion circuit.

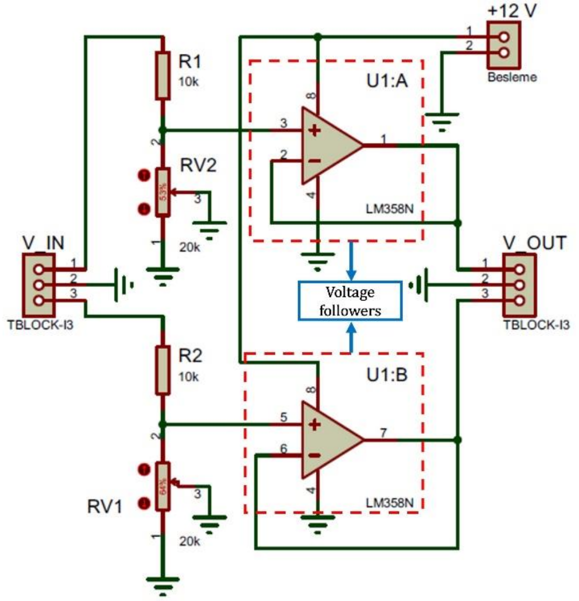

Figure 8. The feedback circuit with voltage follower circuits.

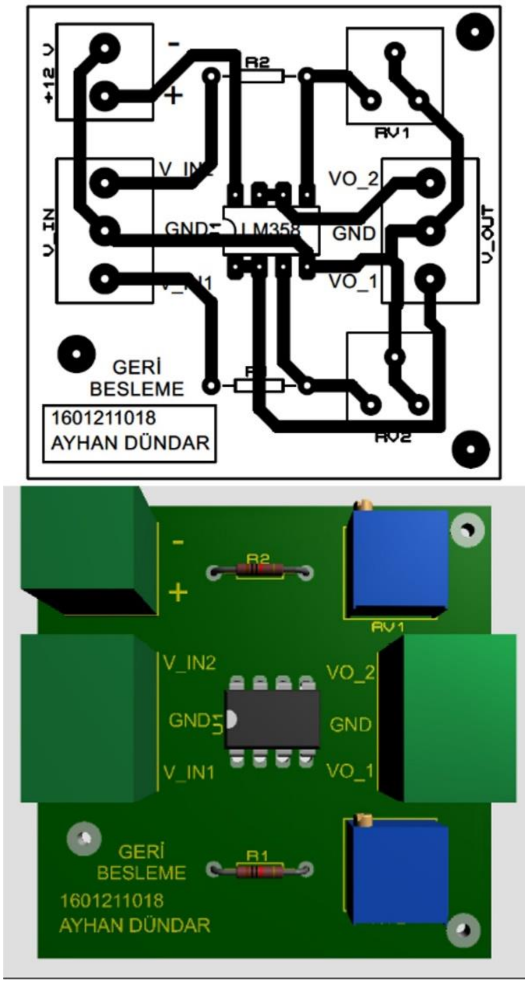

Figure 9. PCB layout diagram and 3D model of the feedback circuit

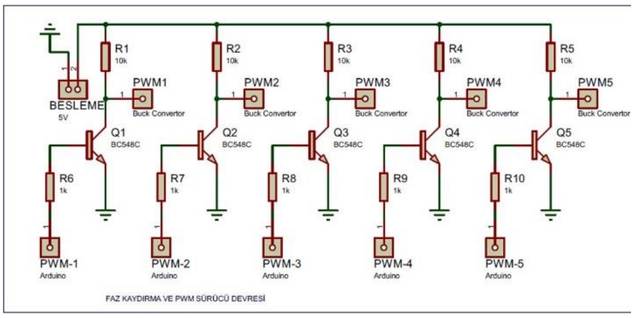

Figure 10. PWM driver and signal inversion circuit.

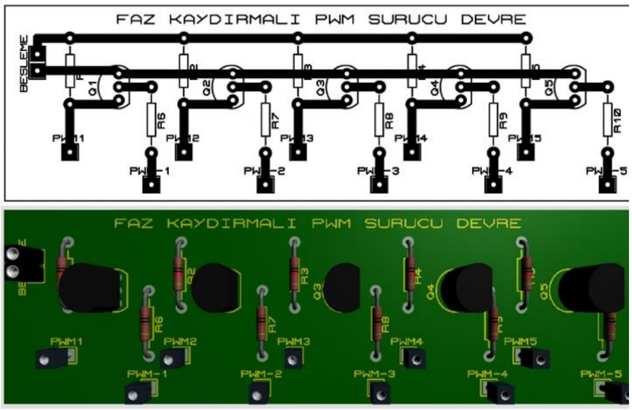

Figure 11. PCB layout diagram and 3D model of the signal inversion circuit

2.6. Arduino MEGA 2560 development card

In this study, Arduino MEGA 2560 development card has been used to acquire and process of the sensor data. These data are utilized in the devised algorithm, which is embedded to Arduino MEGA 2560 via MATLAB/Simulink, to control the illumination of the LEDs thanks to the DC/DC step-down converter and its driver. Arduino MEGA 2560 is an open-source microcontroller board based on ATmega2560 processor. The operating speed of the card is 16 MHz. It has 54 digital input/output ports, 15 of which can be used as PWM output ports. The Mega2560 has 16 analog inputs with 10-bit resolution each. They normally operate in the 0-5 V range. The used Arduino MEGA 2560 is shown in Fig. 12.

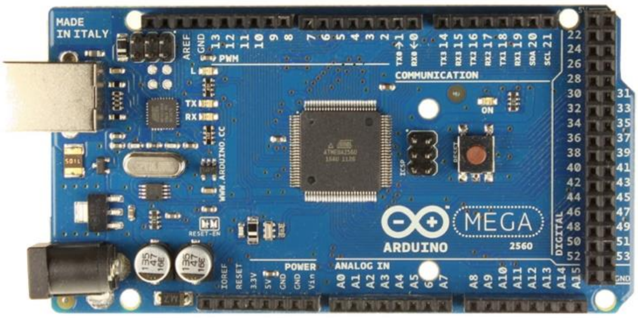

Figure 12. Arduino MEGA 2560 development card

2.7. Devised real time PC controlled demonstration platform

The hardware of the devised real time PC-controlled demonstration platform to develop and to test dynamic LED dimming-based highway tunnel lighting control system is shown in the Fig. 13. The parts of the platform which are labeled by numbers are introduced in follows.

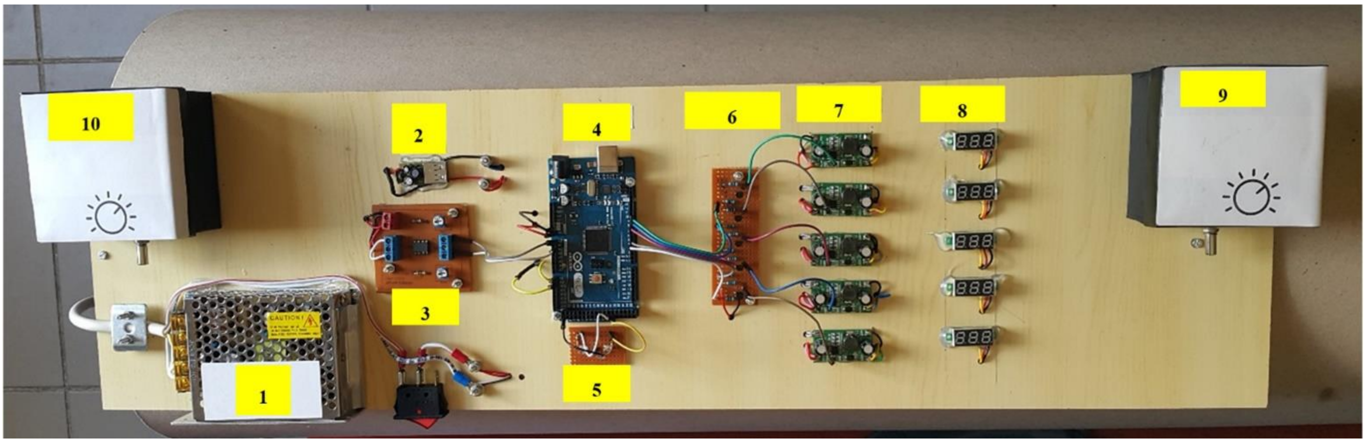

Figure 13. Devised Real Time PC Controlled Demonstration Platform

1: Power Supply (12V, 60W)
2: 5V 3A DC/DC step-down voltage regulator which is used to power supply the Arduino card
3: The feedback circuit
4: Arduino MEGA 2560
5: Sensor to sense day and night
6: PWM driver and signal inversion circuit
7: DC/DC step-down converters which drive the LEDs in the tunnel
8: DC voltmeters shows the voltage of the LEDs located in the different zones of the tunnel
9: Illumination sensor to sense brightness in exit exterior zone of the tunnel
10: Illumination sensor to sense brightness in entrance exterior zone of the tunnel

2.8. Flowchart of the simulation

The flowchart of the simulation which is uploaded to the Arduino MEGA2560 card is shown in Fig. 14. The operation mode of the system is controlled by "Is less than 750?" condition statement which is given in the flowchart of the simulation. The 750 value is a threshold value, and it determines the operation condition as night or day. The value which is determined as 750 has been specified experimentally by trial-error approach such that the value represents the night conditions in the experimental setup.

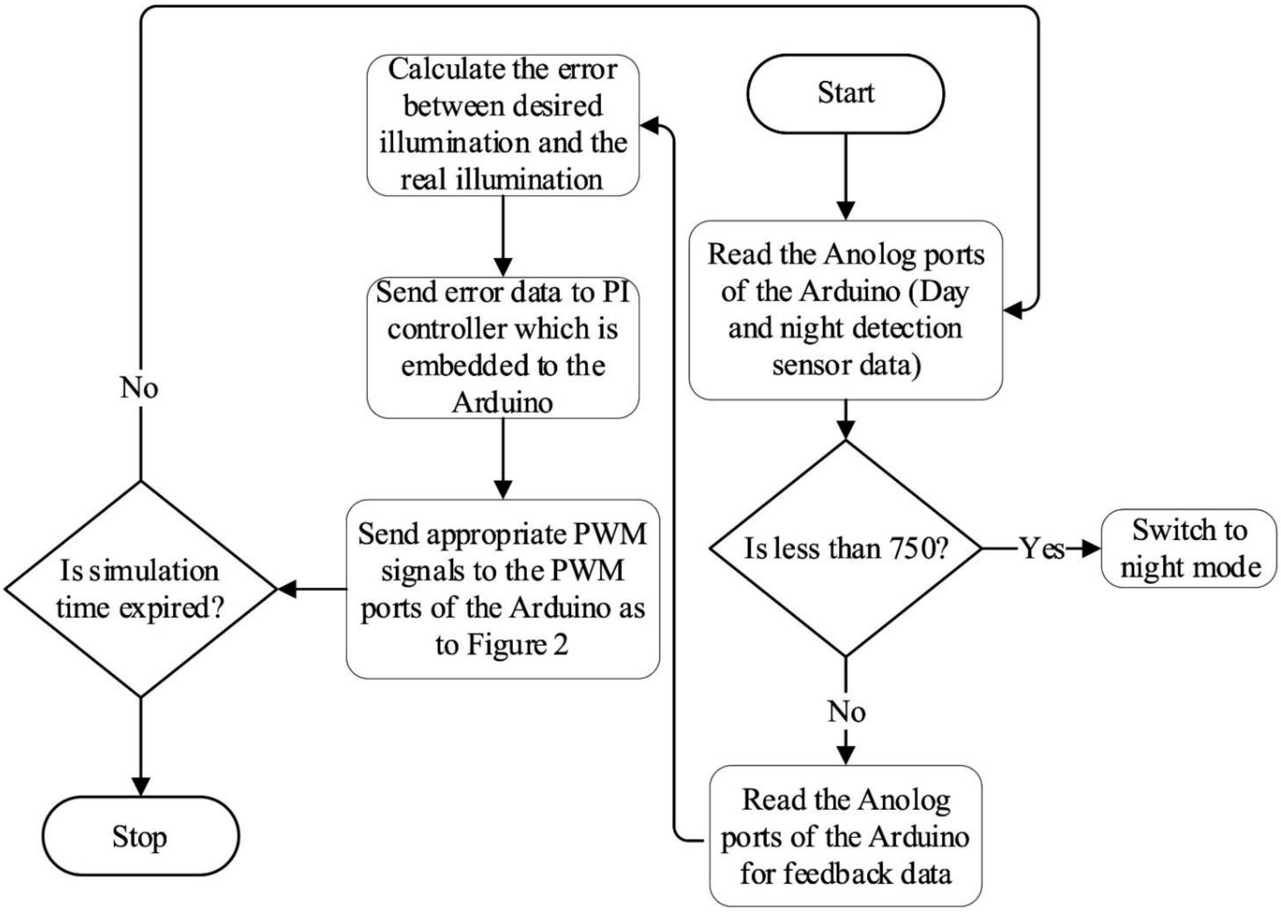

Figure 14. Flowchart of the simulation

3. Results

Some of obtaining the data set through in the case study are presented in Table 1. The PI output is converted to 8-bit data, which is the operating range of Arduino PWM ports as shown in Fig.2. In the system, the lighting levels of the access zone, the transition zone and the interior zone are controlled by PWM-10, PWM-9 and PWM-8, respectively. Since the PWM-10 value should be the same as the outdoor lighting value, the PI output is directly connected to this port and the required value of feedback is taken from this port.

The illumination level of the transition zone has been determined as 50% of the access zone. So, 50% of the PI output value is sent to PWM-9 port. The illumination level of the interior zone has been determined as 25% of the access zone. So, 25% of the PI output value is sent to PWM-8 port. Although it is not shown in Table 1, illumination control of the tunnel's exit zone has been controlled in the same manner as above rates.

As it can be seen in Table 1, A8 is the analog input port of the Arduino, and the actual light value is read from this port. When the table is carefully examined, it is shown that the value 1023 is the 10-bit input value of the Arduino and represents a maximum voltage of 5 V. When the value of the A8 port decreases, A0 feedback port is constantly brought to the A8 value via the PI controller. In addition, it is seen that the values decrease in the input of PWM blocks due to the decreasing amount of light. This shows that the amount of light emitted by the LEDs in the tunnel is reduced by the DC/DC step-down converter, which is connected to the PWM outputs. The results of the above-mentioned operation are also can be seen in the sixth column of the Table 1 which presents the voltage (Volt) of the led whose driver is connected to the PWM 10 port.

Thanks to the day and night transition algorithm, when the A8 input value falls below 750, it is seen that LED lightings in the tunnel increase from the tunnel entrance to the interior area. Then they decrease the light level from the middle area to the exit.

Fig. 15 presents the PI controller output changes in the case study. Since the light level, which are read from A8 Port is at the maximum value at the beginning the simulation, PI output is equal to zero. As it can be seen clearly from the Fig. 15, the decreasing of light while over time during the simulation cause changes in the output of the PI controller.

Table 1. Some of obtained data set through a case study

Illumination sensor data in entrance exterior zone		**Feedback**	**Error**	**PI Output**	**Input of PWM blocks which drive the LEDs. (The measured points are given in the Fig. 2 as a, b and c)**			**The voltage (Volt) of the led whose driver is connected to the PWM 10 port**	**Interpreted lighting level for Port (A8)**
Port (A8) Data as 10 Bit	Volt	**Port (A0)** Data as 10 Bit			**PWM-10**	**PWM-9**	**PWM-8**		
1023	5	1023	0	0,000021	255	127.5	63.75	12	Max
1000	4.89	996	4	164.4	91.81	4587	22.92	11.73	High
990	4.84	988	2	170.7	84.77	42.11	20.77	11.61	
980	4.79	978	2	172.7	79.44	40.08	20	11.50	
970	4.74	969	1	178.9	75.53	38.31	18.91	11.38	
940	4.59	939	1	182.9	72.13	35.81	17.99	11.03	Medium
910	4.45	908	2	187.3	68.12	33.98	16.67	10.67	
890	4.35	887	3	190.6	64.97	32.44	15.92	10.44	
870	4.25	869	1	193.8	61.99	30.91	15.06	10.21	
840	4.11	839	1	200.2	54.67	27.71	13.98	9.85	Low
810	3.96	808	2	210.8	44.87	22.75	11.32	9.50	
790	3.86	787	3	222.5	34.63	16.12	8.31	9.27	
760	3.71	758	2	239.55	16.34	8.68	4.14	8.91	
750	3.67	Transition zone for night and day (Night < 750 < Day)							
<750		Constant light level for night conditions			64	128	255	10.28	Medium

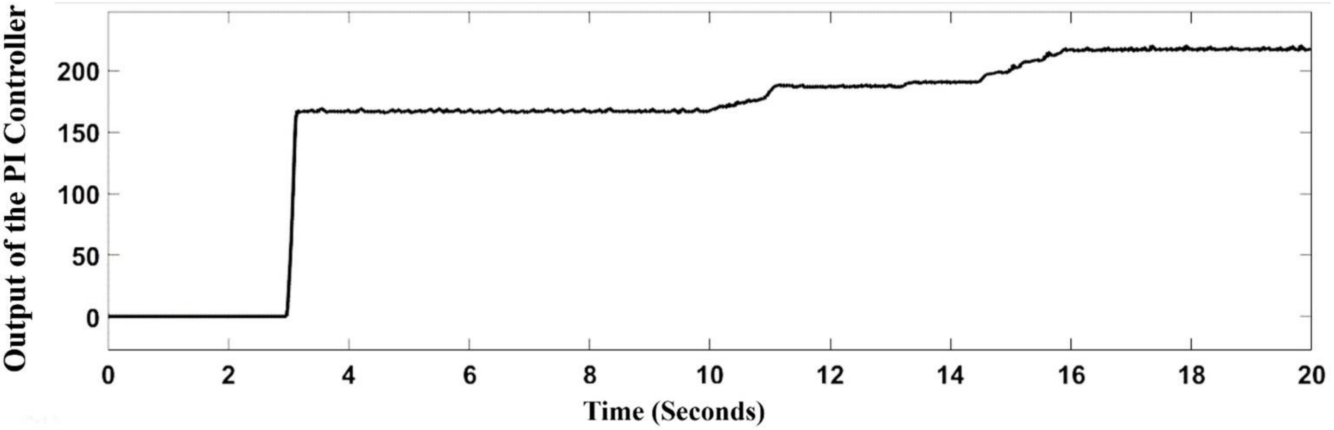

Figure 15. Changes of PI output in the case study

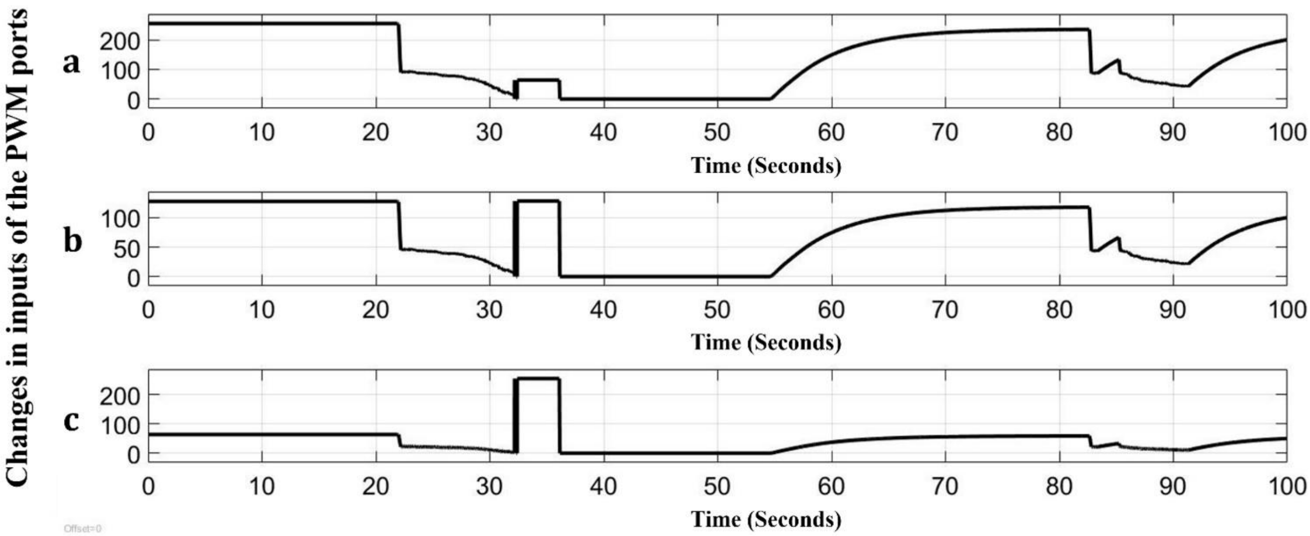

Figure 16. Changes in inputs of the PWM ports in the case study

In Fig. 16, changes in inputs of the PWM ports in the case study are presented. These data have been logged for following scenario. The platform has been tested at the maximum amount of external illumination about 22 seconds. Then the external illumination is decreased, and it has been observed that there is a decrease in inputs of the PWM ports. At the 32nd seconds, the system has been switched to the night mode, and it has been remained in the night mode for about 5 seconds. At the 37th seconds, the system has been switched to the day mode, and the external illumination has been increased to maximum outdoor lighting level in approximately 70 seconds. Between the 80th and 100th seconds, the system has been simulated as if a cloudy weather had occurred such that the external illumination level is undulated.

It can be noticed that from the Fig. 16, when the input of the PWM-10 value takes the maximum value of 255, the input of PWM-9 value takes the maximum value of 128 and the input of PWM-8 value takes the maximum value of 64. The case results prove that the illumination level decreases dynamically from the entrance of the tunnel to the interior zone according to the external lighting level changes, as it proposed in this study.

4. Conclusion

In this study, an LED (Light Emitting Diode) based dynamic tunnel lighting approach has been designed and implemented through devising real time software-controlled hardware. The parts of the proposed platform have been introduced and detailed in order to help with some upgrade studies in the future. The devised system has been tested in some case studies to see the effectiveness of it. The case study results have been discussed and introduced. The results show that the system is performed properly. The devised system can be upgraded and utilized for advanced control studies thanks to its PC and simulation environment connection capability. In the future, it is planned that to develop an advanced controller and to test them through this platform. Also, this platform can be used for tunnel lighting and control practices in some courses in the Electrical and Electronics Engineering Departments.

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Author contributions

Recep Çakmak: Conceptualization, Methodology, Visualization, Simulation, Investigation, Writing-Original draft, Writing-Reviewing and Editing. **Ayhan Dündar:** Simulation, Hardware Implementation and Investigation.

Conflicts of interest

The authors declare no conflicts of interest.

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