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Research Article

A Developed Tunnel Ventilation System Modeling for an Intelligent Transportation System

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This paper presents a Laplace transform model for an urban tunnel ventilation system. This model allows one to witness higher performance for supervisory control and data acquisition (SCADA) in terms of monitoring and control of an urban area tunnel based on measurement systems. This proposed model illustrates the ventilation control system framework as well as the emergency response system for urban area tunnels such that smoother controllability and higher security in the operation of tunnels can be envisioned. The salient contributions of this work can be stated as a novel method for modeling tunnel ventilation systems and the implementation of an emergency response plan for a futuristic intelligent transportation system. The simulation results exhibit that the proposed model outperforms the ventilation system in the high-density traffic jams and further the efficient operation of the tunnel. Likewise, comparison results and experimental results are addressed to emphasize the validation of this method and to be helpful in proving the reliability of the results obtained in this study. These results show that the ventilation control system reaches the desired CO value either in high-traffic volume conditions or in normal traffic conditions.

1. Introduction

1.1. Problem and Procedure Definition. Nowadays, with rapid growth in population and with the development of human areas, the volume of the urban has traffic increased intensively. Researchers and engineers believe that one of the main effective methods to solve this problem is the implementation of an efficient intelligent transportation system. Besides this problem, the security requirement of the urban area tunnel (UAT) necessitates one to pay more attention to this problem. The first step, in maintaining the security of any urban tunnel, is to have a data acquisition system and to have an intelligent control system. The combination of these two systems is named as supervisory control and data acquisition (SCADA). The main characteristics of the advanced SCADA system consist of security, reliability, controllability, and safety. The SCADA systems are more applicable in electric power systems, water treatment systems, irrigation systems, oil and gas refineries, and petrochemical industries [1].

The economic benefit of using the SCADA is remarkably large. The operation of the tunnel is performed easily by SCADA. The SCADA system not only helps to make correct decisions for operators but also decreases the maintenance cost [2]. In addition, the emergency response plan, in fire conditions, has the main role in the rescue of humans from urban tunnels in emergency modes. This role is related to social welfare in any sustainable city. The urgent result of using the SCADA system on the urban area tunnel is mainly the reduction of cost. In fact, because the urban area tunnels are faced with high traffic conditions, the ventilation system is more important. The capital cost for implementation of the system is approximately a million dollar only for the control and SCADA system per km of tunnel length. Absolutely, this cost is less significant than the health damage costs and psychological damage costs.

1.2. Literature Review. There are many research studies which are related to the methods for tunnel ventilation control systems [3–7]. This system works both on normal ventilation conditions and emergency ventilation conditions. In normal conditions, the carbon monoxide (CO) parameter and the air velocity parameter are monitored by a smart control system on SCADA and the related commands are made to the ventilation system. The observed carbon monoxide value inside the tunnel must be lower than the threshold value which is determined by a national standard and the Permanent International Association of Road Congresses (PIARC) [8–10]. Also, there are some research studies for managing transportation systems using the artificial intelligence (AI) method and the Internet of things (IoT) [11–22].

In [13], a form of genetic algorithm is used to improve the traffic conditions in the Manhattan road networks. This algorithm is powered by a parallel hybrid bi-objective method. A grey prediction algorithm shows research on highway tunnel ventilation control in [14]. This grey prediction algorithm considers Internet of Things (IOT) to implement the highway tunnel ventilation control system. An analysis of smoke movement, in tilted tunnel fires with longitudinal ventilation, studied in [15]. [16] shows effects of both longitudinal slope and traffic volume on user safety in a fire accident. There are some research studies on numerical studies on fire smoke movement and ventilation in in [17, 18, 20]. Risk analysis of one-way road tunnel tubes used for bidirectional traffic under fire scenarios was studied in [19]. In [21], a sustainable safety management framework for connected vehicles is proposed by integrating blockchain. It introduces smart transportation equipment called an AI-enabled vehicle smart device (AVSD) for vehicular communication. The authors in [22] highlight the problem that road transport in India is very unsafe, and put forward a proposed model of blockchain-assisted Internet of vehicles as a solution to tackle this issue.

All the recent research studies, on objects of ventilation systems in fire conditions and/or in normal conditions, illustrate the importance of the urban tunnel ventilation system as a part of intelligent transportation systems in urban areas.

1.3. Procedure and Methodology. This paper describes how to work the ventilation subsystem in a SCADA system. In order to have a satisfactory control scheme and to have robust control and also to have a usefulness control system, the proportional-integral (PI) controller is used to control the closed-loop tunnel ventilation control system [23]. The control system includes sensors which are located throughout the tunnel, programmable logic controllers (PLCs) which are located in the technical room, jet fans which are located in the tunnel, and the human-machine interface (HMI) which is located in the control center room. Another important system of SCADA is the emergency response system (ERS). This system consists of twenty-eight scenarios. Each scenario is initiated by a reason of events and then is triggered by measuring the input signal and then the system response is performed according to the design of the system. The paper explains how to implement each scenario in an urban area tunnel SCADA system.

1.4. Highlights and Contributions. In order to specify the contributions and highlights of the paper, this subsection is added to the Introduction. The important contributions of this paper are highlighted as follows:

(i) Modeling of tunnel ventilation system in Laplace transform framework

(ii) Developing the S-domain transfer function of the PLC system and gathering the related adequate parameters

(iii) Developing the S-domain transfer function of the jet fan system and gathering the related adequate parameters

(iv) Developing the S-domain transfer function of the tunnel plant system and gathering the related adequate parameters

(v) Developing the S-domain transfer function of the CO measurement system and gathering the related adequate parameters

(vi) Developing the S-domain transfer function of the road traffic system and gathering the related adequate parameters

(vii) Modeling the emergency response system in emergency incidents and gathering the related adequate parameters

(viii) Tuning the PI control system and gathering the related adequate PI coefficients

(ix) Reducing waste time in order to decay CO pollution in high-traffic density

(x) Disregarding human errors in the operation of tunnels at emergency conditions with the implementation of ERS

(xi) Subduing the maintenance cost.

1.5. Paper Organization. The rest of the paper is organized as follows. Section 2 describes the structure of the urban area tunnel SCADA system. The Proposed method for emergency response system scenarios design is briefly reviewed in Section 3. Section 4 discusses the proposed control model of the tunnel ventilation system. The performance evaluations are illustrated in Section 5. Section 6 concludes the paper.

2. Structure of the Urban Area Tunnel SCADA System

2.1. Measurement Systems. Measurement systems are developed to cover all requirements for urban area tunnel SCADA systems. They consist of the following:

(i) Sensor-based measurement systems include visibility sensor, smoke sensor, fire sensor, CO sensor, wind velocity sensor, temperature sensor, and pressure sensor.

(ii) Intelligent-based measurement systems include automatic incident detection (AID), luminance measurement (LM), linear heat detection (LHD), and traffic detection (TD).

All signals, which are measured by each device, must be transferred to a control center. This transfer is performed through a remote terminal unit (RTU) and/or through a direct connection to the control center. The first part of signals must be connected to the RTU with one of the following methods. The first is the hardwire method with a 4–20 milliampere current signal. The second is the protocol method. The most popular protocols are Modbus and/or IEC 104 which are used for data transferring.

2.2. Remote Terminal Unit. The remote terminal unit is an interface device between measurement systems and the control center. This device collects all input signals from measurement systems and forwards them to the control center. It also sends all output signals from the control center to field devices. The input signals can be connected to a remote terminal unit through hardwire or through communication protocols. Figure 1 shows the structure of a typical remote terminal unit. It consists of three main sections. The first section is the power supply section. The second section is the central processor unit and the third section is the input and output modules.

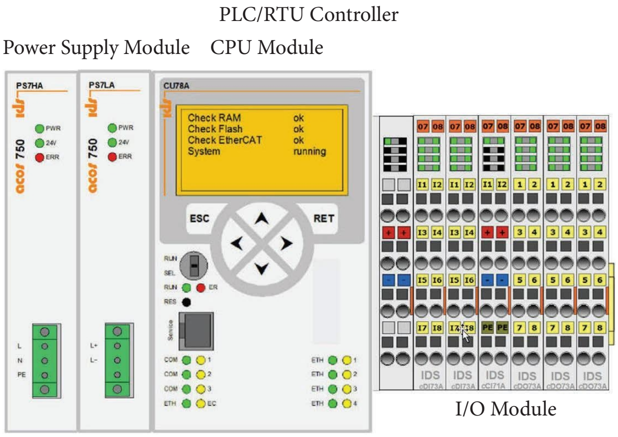

Figure 1: Structure of the remote terminal unit.

2.3. Communication System. The communication system in the UAT system is designed based on the local area network (LAN). There are two fiber optic rings through the tunnel to facilitate communication among field devices, RTUs, and control centers. Some of the most popular protocols for communication between field devices and RTUs are as follows:

(i) Modbus/RS-485
(ii) Modbus/TCP-IP
(iii) IEC 870-5-104
(iv) SNMP-Ver. 2.0

2.4. Master Control Center. In order to have a high security and high reliability, two control centers are designed and implemented for urban area tunnels. Master control centers consist of two main server computers, one historical server computer, three operator workstations, one video wall system, one GPS, two reporting printers, and two LAN systems. The structure of the main control center and backup control center is depicted in Figure 2. The location of these control centers is designed to be located on the two sides of the tunnel.

3. The Proposed Method for Emergency Response System Scenarios Design

A main criterion of the measurement system of the SCADA system is an adaptation with an emergency response system to have a high reliability and security in emergency conditions. Therefore, there are many types of scenarios which can be defined for the operation of a tunnel. These scenarios will be designed in different groups in order to simplify recognizing, prioritizing, and managing scenarios. The list of these groups and the related events consist of four sections. The first section is an incident event which includes three subsections: fire detection, traffic incident detection, and air/light quality control incident. The second section is normal operation. The third section is about malfunctions and failures. The last section is maintenance. Also, each scenario of the emergency response system is designed and implemented into three items. The first item is a definition and reason of the event. In this item, the event will be described and all the reasons which can raise the event will be declared. The second item is trigger points. These trigger points will be generated by measurement systems. The third item is system response action. In the third item, the scenario of system responses and the reactions of the operator will be declared and described. This type of design is an effective method to help the operator to make a correct decision in emergency conditions. Based on these categorizations, in this emergency response system, twenty-eight scenarios are designed to cover all operation requirements. These scenarios are listed as follows:

The first section of scenarios/item1: fire detection group:

(1) Fire detection by longitudinal fiber detection (LFD) cable or emergency push button
(2) Fire detection in cross passage
(3) Fire extinguisher cabinet door opening
(4) Fire/smoke detection inside the tunnel by an automatic incident detection system
(5) Fire scenario:
(6) Fire detection in substation
(7) Pump station activated

The first section of scenarios/item2: traffic incident detection group:

(1) Stopped vehicle detection by the AID system
(2) Drop object detection by the AID system

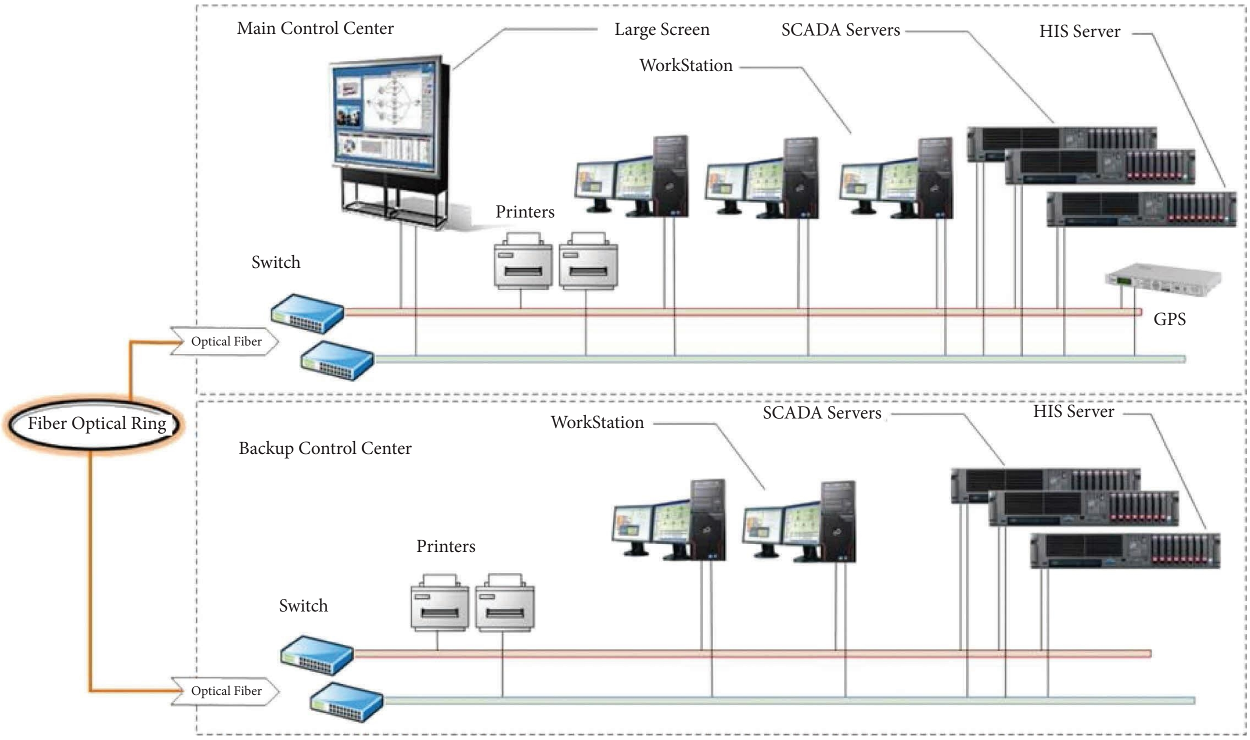

Figure 2: Structure of the main control center and backup control center.

(3) Traffic obstruction detection by the AID system
(4) Wrong-way vehicle detection by the AID system
(5) Pedestrian in tunnel tube detected by the AID system
(6) Traffic accident scenario
(7) Emergency evacuation scenario

The first section of scenarios/item3: air and light quality control incident group:

(1) Exceeded the limit values of visibility parameter
(2) Exceeded the limit value for the luminance detector (black hole effect)
(3) Exceeded limit values of CO
(4) Exceeded maximum limit for side wind

The second section of scenarios: normal operation group:

(1) Niche (small technical room located in the tunnel) door open
(2) Emergency cross-pass door open
(3) S.O.S phone call inside the tunnel
(4) S.O.S phone call outside the tunnel

The third section of scenarios/item1: malfunction and failures group:

(1) Power failure
(2) Tunnel lighting failure
(3) Subsystem malfunction
(4) Wetness by the weather system
(5) Wetness by the flood detection sensor

Third section/item2: maintenance group:

(1) Maintenance scenario

Figure 3 shows a flowchart of fire detection by longitudinal fiber detection (LFD) cable or emergency push button scenario in the detailed mode as an example of an emergency scenario. When there is a fire in the tunnel, two alarms can be generated and reported to the SCADA system. The first alarm can be generated by the LFD system, and it sends the appropriate fire zone number to the control system. The second alarm can be generated by a person pushing a button inside the tunnel in order to report a fire. It should be noted that there can be many push buttons in each fire-detected zone therefore the fire alarm control system will report only the fire-detected zone number. Appropriate fire alarms, according to the fire zone will be presented in the alarm list of SCADA software.

The fire alarm system layer, in the operator workstation, will be presented in the graphic user interface. The videostream of all available cameras, inside the detected fire zone, will be shown in the large screen display in the control center room. If the event is detected by LFD then a dialogue pops up and shows the event name, tube name, and detected fire zone number to the operator and immediately the “fire scenario” will start automatically. However, if the event is detected by emergency push buttons, then a dialogue pops up and shows the event name, tube name, and detected fire zone number to the operator. When the operator pushes the Ok button, then “fire scenario” will be called and started. The operator also can cancel the dialogue, and then no further scenario will be started. It is noted that if the operator does not push the button for 20 seconds, then the “fire scenario” will be started automatically.

Figure 4 describes the flowchart of a maintenance scenario in the detailed mode as an example of each scenario. This scenario is called by other scenarios. Also, it is possible for this scenario to be called manually by the operator, when the maintenance operation in the tunnel is needed. A dialogue box pops up in this scenario. It shows information about the maintenance scenario. In this dialogue box, the operator is asked to follow the complimentary steps by pushing the OK button. After confirmation from the operator, the scenario pops up another dialogue and asks the operator to follow further actions by choosing one of the following buttons: the north tube button, the south tube button, and the exit button. After the selection of the operator, the scenario shows another dialogue box and shows the information about the selected tube for maintenance operation. The following options are available for the operator to continue: close tube, close left lane, close right lane, reset scenario, and exit scenario. In the reset state, traffic signalization and announcement system are changed to the state before the scenario was started. In the exit state, the scenario is finished and no further action is requested.

4. The Proposed Control System for the Tunnel Ventilation System

The operation of the ventilation system, in urban area tunnels, has more dependency on the measurement system. The ventilation measurement system includes sensors, PLC, jet fans, control panel of jet fans, and communication systems. The location of these sensors affects the performance of the ventilation system in emergency mode or in severe ventilation conditions, remarkably. Either the location of these sensors or the number of these sensors can create a malfunction in the ventilation system. Therefore, it is needed to determine the optimum number and the optimum location of these sensors. The shape of a cross-section of the tunnel and the length of the tunnel are two main parameters that can affect the location of these sensors and the number of them. In this paper, we assume that the location of sensors and the number of sensors are fixed and it is needed for the future research work to have optimum values of them.

In this paper, a newly constructed urban area tunnel, which is located in the west of Tehran/Iran, is selected to analyse the performance of the proposed model. This tunnel operates with the longitudinal ventilation system in operation and there is no central smoke exhaust system in the emergency mode. The parameters of this tunnel and the parameters of jet fans are given in Tables 1 and 2, respectively. The length of this tunnel is almost 1000 m and the axe of the tunnel is in the west-east direction (in the natural wind direction). As a result, it is caused to have a good ventilation performance in the south tube but also to have a weak ventilation performance in the north tube. It is noted that both the impacts of natural wind velocity and the piston effects of vehicles in the tunnel are neglected. In addition, the effects of bad weather conditions such as typhoons on the measurement data also were neglected in the internal tunnel ventilation measurement system. Figure 5 shows a schematic overview of the tunnel plant ventilation control model.

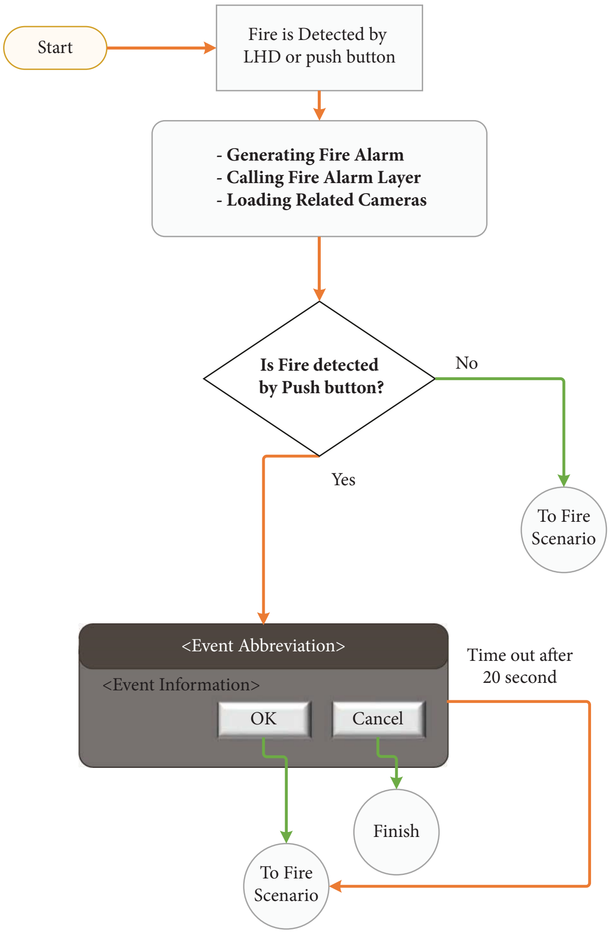

Figure 3: Flowchart of fire detection by longitudinal fiber detection (LFD) cable or emergency push button scenario.

The proposed ventilation system model is categorized into five sections. These sections are PLC, jet fans, tunnel plant, traffic volume, and sensors. Each section is modeled as a single input-single output system. In order to build this proposed model, an identification process is defined to achieve a transfer function for each section. In this process, the parameters of the system are determined by an experimental data [24–26]. In this identification process, any linearization of nonlinear systems and/or any simplification of complicated systems are made to achieve an equivalent linear system. In the following, the results of this identification are illustrated.

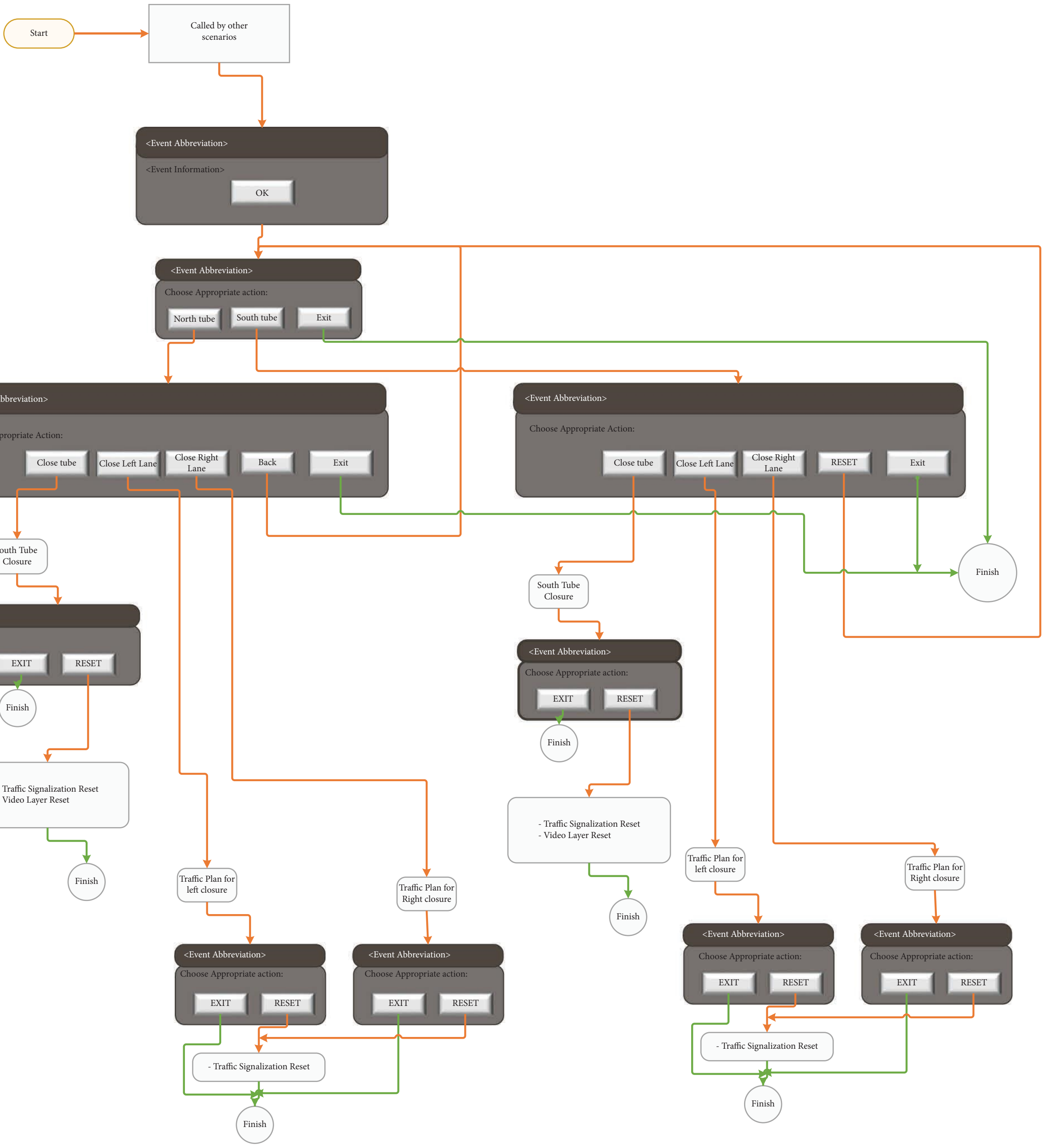

Figure 4: Flowchart of the maintenance scenario.

Table 1: Parameters and specifications of the tunnel.

No. of tubes	2
Length (m)	1000
Width of the portal (m)	16.08
Height of the portal (m)	8.83
No. of lanes per tube	3
Max. permissible traffic speed (km/h)	70
No. of jet fans	6 pairs/tube
Distance between two pair jet fans (m)	150
No. of sensor	3/tube
Distance between two sensors (m)	375

Table 2: Parameters of jet fan.

No. of poles	4
Thrust (N)	800
Outlet velocity (m/s)	30
Nominal speed (rpm)/(rad/s)	1460/152
Volume flow rate (m^3/h)	84800
Shaft power (kW)	21.5
Max. motor power (kW)	30
Nominal current (A)	67.8
Sound power level (dB(A))	100
Weight (kg)	700

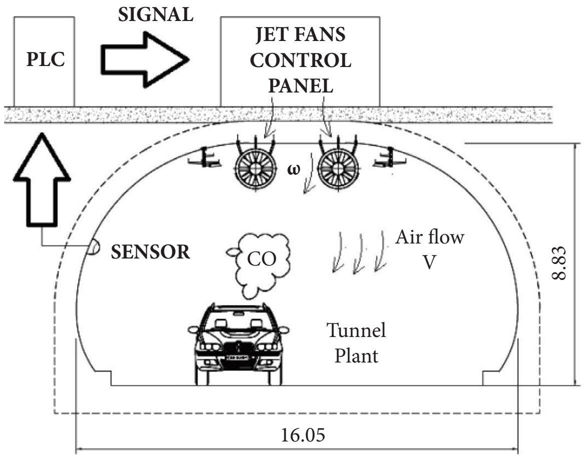

Figure 5: Schematic overview of the tunnel plant ventilation control model.

4.1. PLC. The CO value of the tunnel is controlled by the PLC under the closed-loop PI control method. The PLC connects to CO sensors and the measured CO value is compared with the CO reference value in the PLC. The result of this comparison is an error signal. This error signal is fed into the PI controller.

The Laplace transfer function for the PI controller is shown in the following equation:

$$F_{\mathrm{PI}}(S) = k_P\left(1 + \frac{1}{T_i S}\right). \tag{1}$$

In this controller, the proportional coefficient value is denoted by k_P and its value is set to 0.003 and the integral coefficient value is denoted by T_i and its value is set to 1.

4.2. Jet Fan. The input variable of the jet fan is a control signal. The signal is generated by the PI controller system and the output of the jet fan is the rotational speed of the shaft of the jet fan. The jet fan system is modeled by the first-order system with k_j as the numerator coefficient and T_j as the time constant. The Laplace transfer function for this system is shown in the following equation:

$$F_{JF}(S) = \frac{k_j}{1 + T_j S}. \tag{2}$$

For the mentioned tunnel system, the T_j time constant for the jet fan is one second and the k_j numerator coefficient is 150 radians per second.

4.3. Tunnel Plant. The input variable of the tunnel plant is the rotational speed of the jet fan which is generated by the jet fan system and the output of the tunnel plant is the air velocity of the tunnel. The tunnel plant is modeled by a first-order system with k_t as the numerator coefficient and T_t as the time constant. The Laplace transfer function for the tunnel plant is shown in the following equation:

$$F_{TP}(S) = \frac{k_t}{1 + T_t S}. \tag{3}$$

For this tunnel plant, the T_t time constant for the tunnel plant is 166.67 second and the k_t numerator coefficient is 0.0423 meter per second.

4.4. CO Measurement System. The input variable of the CO measurement system is the air velocity of the tunnel which is generated by the jet fan system and the output of the CO measurement system is the CO value. This measurement system is modeled by a first-order system with k_s as the numerator coefficient and T_s as the time constant. The Laplace transfer function for the measurement system is shown in the following equation:

$$F_{\mathrm{CO}}(S) = \frac{k_s}{1 + T_s S}. \tag{4}$$

For this sensor, the T_s time constant of the CO measurement system is 50 second and the k_s numerator coefficient is 2.5 ppm (part per million).

4.5. Traffic System. The input variable of a traffic system is traffic intensity and the output of the traffic system is CO value. This system is modeled by a first-order system with k_v as the numerator coefficient and T_v as the time constant. The Laplace transfer function for the traffic system is shown in the following equation:

$$F_{TS}(S) = \frac{k_v}{1 + T_v S}. \tag{5}$$

For this sensor, the T_v time constant of the traffic system is 100 second and the k_v numerator coefficient is 1 ppm.

According to the related standard as PIARC [8], the maximum CO value is 35 ppm. Therefore, the control system must decrease the CO value with jet fan speed control. This control system uses the average values of the three sensors as a measured value. The control system is a closed-loop control system which uses a PI controller to have a better performance by controlling the CO value to reach the desired value. The desired value of CO is 25 ppm. Figure 6 illustrates the location of the three sensors through the tunnel. In order to have the best performance of the control system, an allocation algorithm for measurement sensors is used to determine the location of each sensor. The block diagram of the tunnel ventilation control system is shown in Figure 7. This block diagram is a closed-loop CO control system with traffic intensity as input of this system.

5. Performance Evaluation

In order to evaluate the performance of the proposed tunnel ventilation control model, the ventilation system is simulated using the MATLAB software in a Simulink environment. This simulation is executed for two conditions. The first condition is for jet fan, tunnel plant, and CO measurement performance evaluation. The second condition is for the proposed closed-loop control system performance evaluation. The following two clauses illustrate these two evaluations.

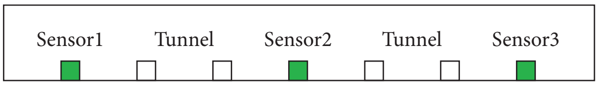

Figure 6: Location of the three sensors in the tunnel.

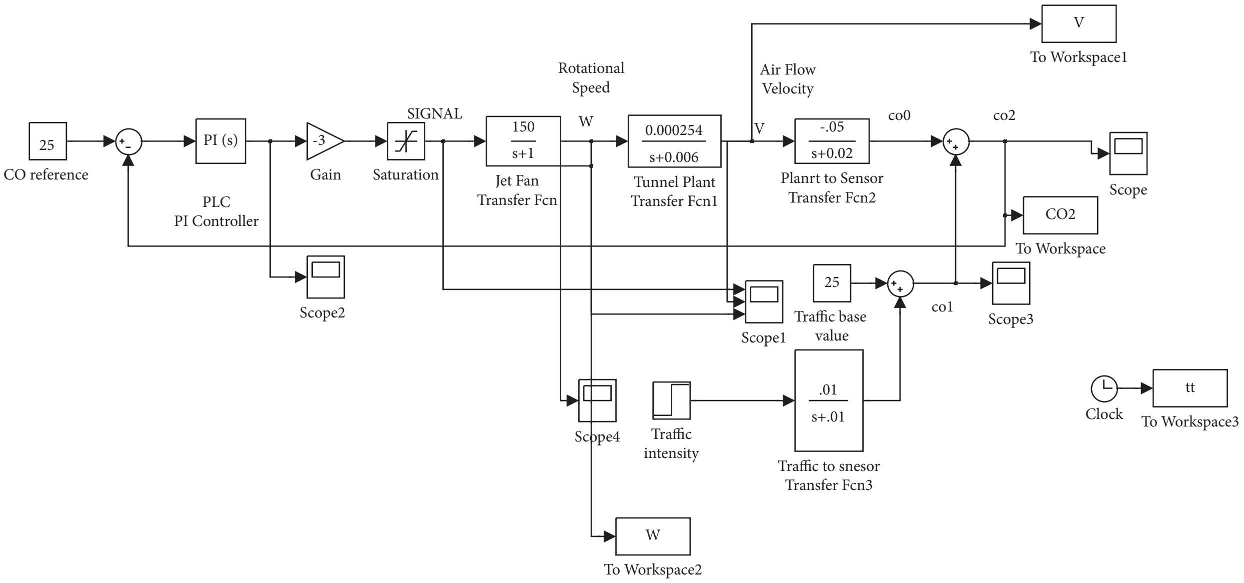

Figure 7: The proposed block diagram of the tunnel ventilation control system.

5.1. Unit-Step Response of Feed-Forward Transfer Function. The unit-step response for the three output values includes the rotational speed of the jet fan, air velocity of the tunnel plant, and the measured CO value of the tunnel plant, which are shown in Figures 8–10, respectively. As shown, the rotational speed output of a jet fan has the exponential form. The acceleration of the jet fan is increased during 5 seconds from zero value up to the rated value using an adjustable speed drive. The air velocity of the tunnel plant reaches to the value of 6 m/s from zero after 1000 seconds (approximately 16.7 minutes). This value can be increased by the piston effect of vehicles and natural wind effects. These effects are neglected in this paper.

It is clear that the ventilation system can reduce the 16 ppm CO value from the base value of the tunnel as shown in Figure 10.

5.2. PI Controller Evaluation in Closed-Loop Control Scheme. In most traditional control systems, to achieve small errors of a system, the closed-loop control system is used for the control system. The PI controller has three features. These features are stability, fast response, and zero steady-state error of PI controllers. The transient response of any control system exhibits the damped oscillation prior to the steady state. Moreover, the overshot and settling time parameters are important parameters for the analysis of the CO level of the tunnel ventilation system. These parameters are somewhat changeable by the PI controller coefficient so that, to have the desired characteristics of outputs, the tuning analysis is required to select the optimum value of these coefficients. In order to evaluate the performance of the control system, it is assumed that the tunnel, in the base case, shows the CO value of 25 ppm and the traffic intensity (traffic volume) gradually grows. Subsequently, the CO value increases to 35 ppm during 500 seconds as an input signal. The three main output signals are monitored for the performance evaluation. For each output signal monitoring, a comparison is performed among the three responses of the control system by changing the parameters of PI controllers. Figure 11 shows the step response curve of the tunnel with changes in traffic intensity for various values of integral coefficient. It illustrates that a higher Ti value causes a higher overshot value and a smaller settling time. Nevertheless, a maximum overshot is found for $Ti = 1$ and thus this value ends at 33 ppm. Based on the results, it is shown that the CO controller can effectively adjust the CO level and it operates massively for reducing the CO content in the tunnel. The simulation time is 3000 seconds (approximately 50 minutes). Technically speaking, the aforementioned figures show that the dynamic behavior of the closed-loop control system has a good performance when the CO final value reaches an acceptable range. However, this range is the acceptable value according to the PIARC standard.

Figure 12 depicts the air velocity value. It increases from the base value to the desired value. In this work, it is assumed that this base value of air velocity is zero. This figure shows that air velocity can increase up to 4 m/s. This value is an appropriate value for removing contaminated toxic gases (especially CO) from inside the tunnel. These gases are generated by the vehicles. The rotational speed of a jet fan is shown in Figure 13. The rotational speed value of the jet fan,

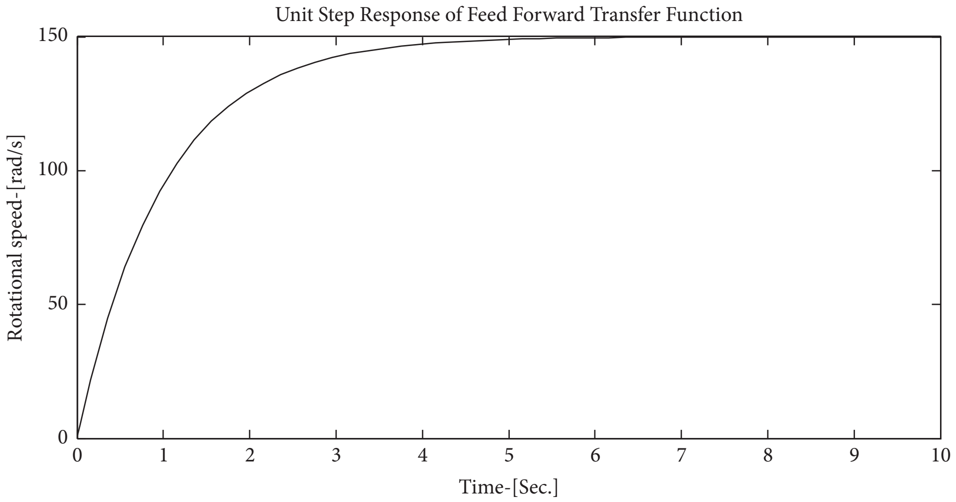

FIGURE 8: Unit-step response of the feed-forward transformer function of the tunnel ventilation control system (rotational speed).

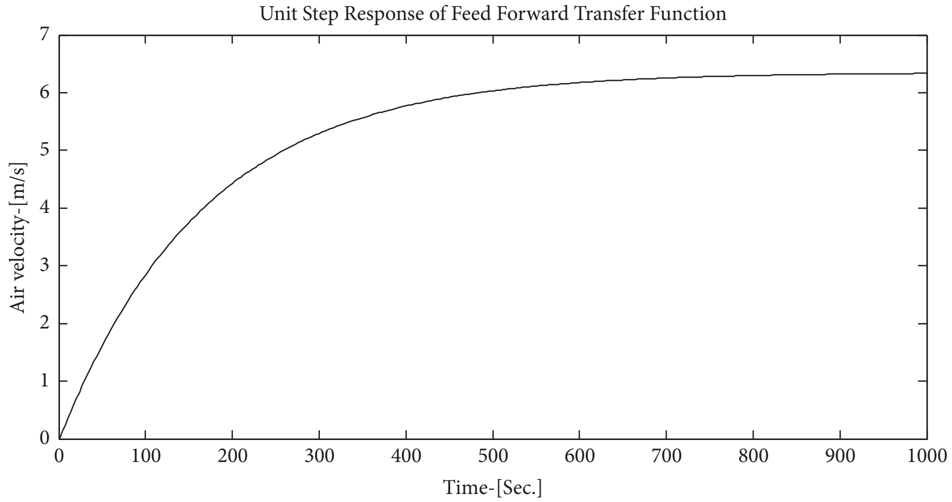

FIGURE 9: Unit -step response of the feed-forward transformer function of the tunnel ventilation control system (air velocity).

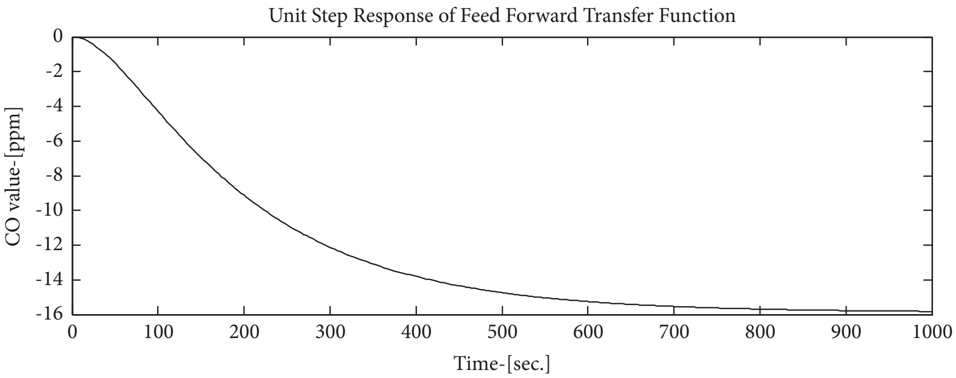

FIGURE 10: Unit-step response of the feed-forward transformer function of the tunnel ventilation control system (measured CO value).

for $Ti = 0.33$, has reached the saturated value. In fact, an adjustable speed drive of the asynchronous motor of a jet fan cannot increase the speed of the jet fan to more than the saturated value because this speed is the highest speed value of the motor. The saturated condition is from 240 s up to 500 s. One of the PI coefficients is *kp*. Figures 14–16 show the outputs of the ventilation control system for varying *kp* values. In the ventilation system, it is preferred to decrease

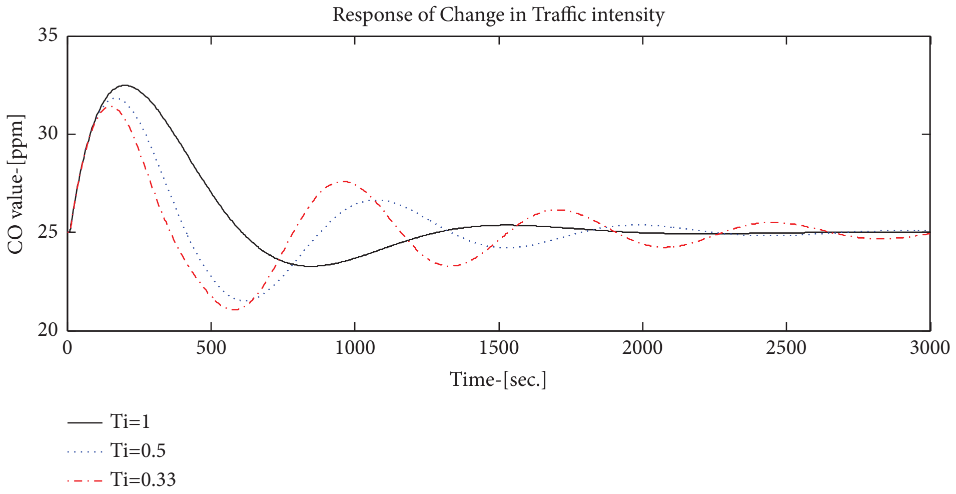

Figure 11: CO response of the tunnel-change in traffic intensity with different integral coefficient values ($Ti = 1$, 0.5, and 0.33).

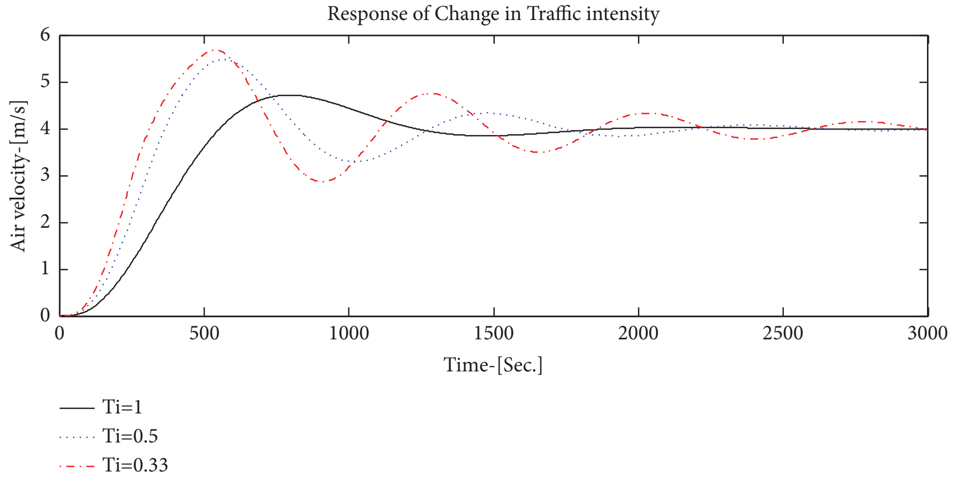

Figure 12: Air velocity response of the tunnel-change in traffic intensity with different integral coefficient values ($Ti = 1$, 0.5, and 0.33).

the CO value in less time so that the result for $kp = 0.01$ is better than the other output values for kp = 0.03 and/or kp = 0.05 (Figure 14).

5.3. Comparison Results. In order to have a better understanding of this paper and to evaluate the good performance of the proposed method, we compared the results of this study with the results of the CO value of the tunnel in [27, 28]. The speed of each jet fan is set to 20 and 25 in [27, 28], respectively. This speed for the proposed method is 25 m/s. The CO value and settling time are considered as output values. These results are illustrated in Table 3.

It can be seen that the settling time of the tunnel in [27, 28] is equal to 170 and 200, respectively, which is equal to 150 in this study. The length of the tunnel for the proposed method is more than the length of the tunnel in [27, 28]. The more length causes it to have more inertia. As a result of Table 3, the CO output value for the proposed method is smaller than the CO value for [27, 28]. The speed of the vehicle is between 30 and 40 in [27] and between 20 and 30 in [28]. Due to light car-dominated traffic, it is the same as neglecting the piston effect of the vehicle. These results show that the proposed method has fastness, effective in clearing CO contamination, and is more reliable.

5.4. Experimental Results. To validate the performance of the proposed model, the real-time experimental results are shown and are compared with the simulated data. The CO values are considered for an analysis. Actual CO outputs are received from the tunnel SCADA system for 400 sample data for one minute time. Data gathering is done in afternoon traffic condition , when the people were intended to return to home with high traffic volume, this high density traffic condition is caused to increase CO pollution in the tunnel. These CO values are shown in Figure 17. The vertical axis of this figure is the CO value with the dimension of part per million (PPM) and the horizontal axis is the time value with a dimension of minute. This figure shows that the CO value

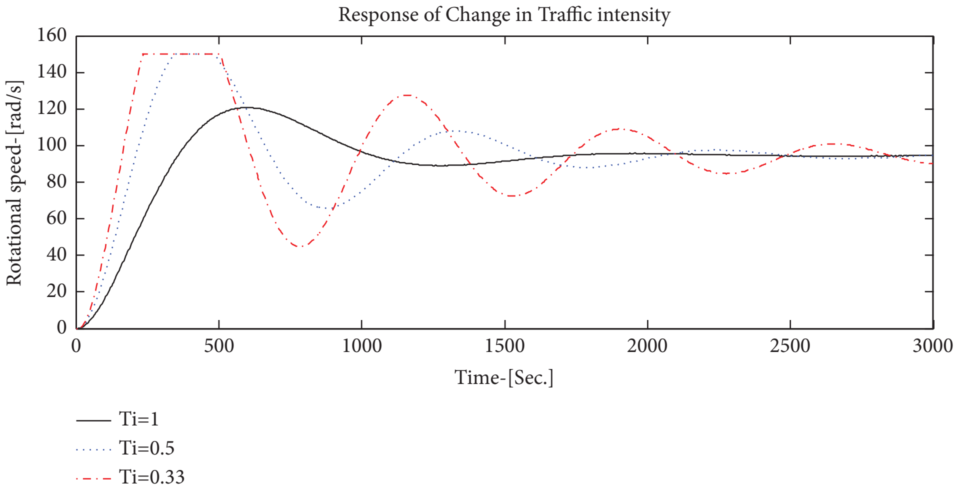

Figure 13: Jet fan rotational speed response of the tunnel-change in traffic intensity with different integral coefficient values ($Ti = 1$, 0.5, and 0.33).

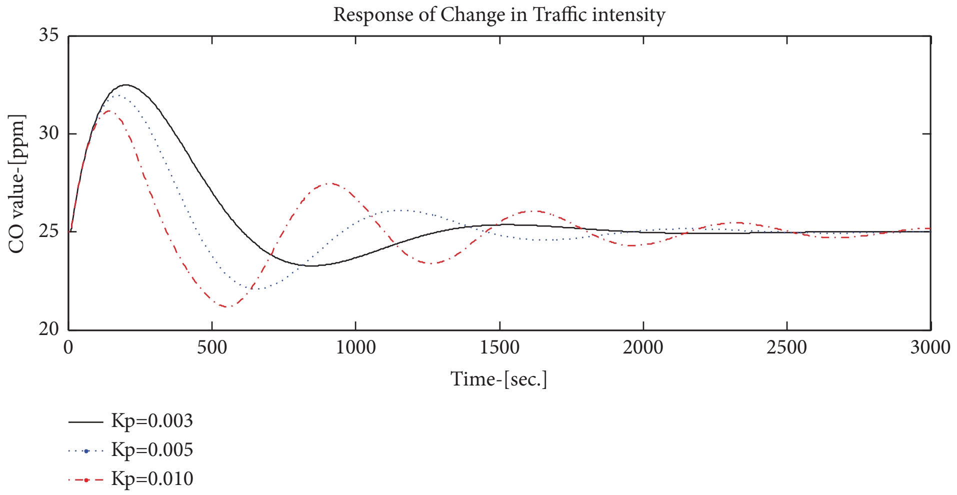

Figure 14: CO response of the tunnel-change in traffic intensity with different proportional coefficient values ($K_P = 0.003$, 0.005, and 0.010).

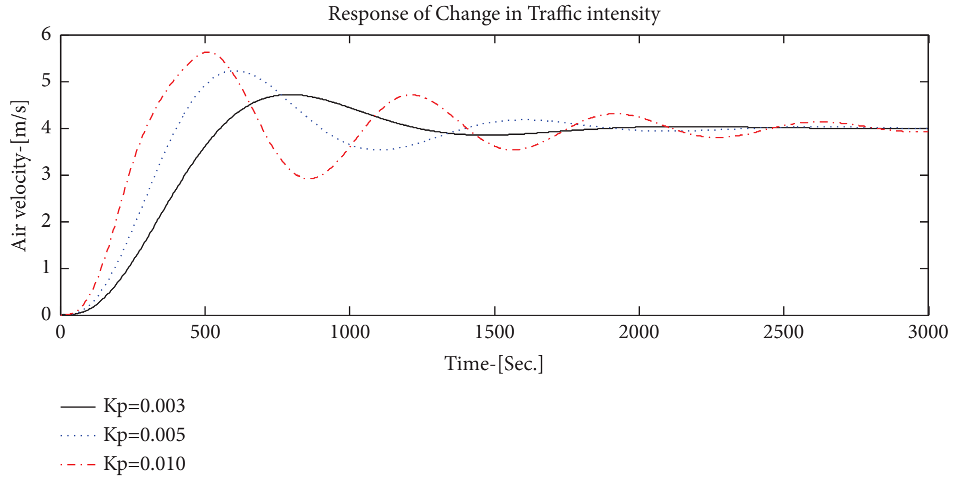

Figure 15: Air velocity response of the tunnel-change in traffic intensity with different proportional coefficient values ($K_P = 0.003$, 0.005, and 0.010).

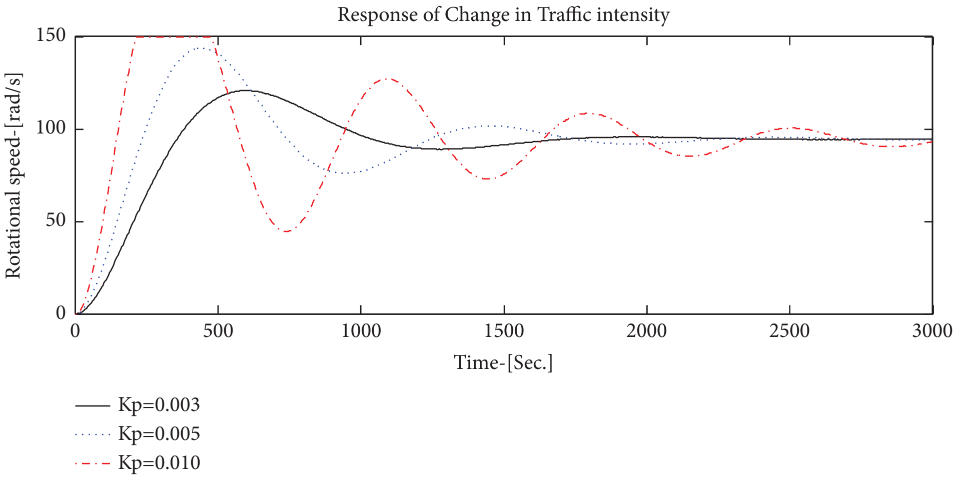

Figure 16: Jet fan rotational speed response of the tunnel-change in traffic intensity with different proportional coefficient values ($K_P = 0.003$, 0.005, and 0.010).

Table 3: The comparison result table.

Description	The proposed method	[27]	[28]
Settling time (s)	150	170	255
CO final value (ppm)	25	28	30
Length of the tunnel (m)	1000	550	750
Jet fan speed (m/s)	30	25	20
Vehicle speed (km/s)	Effects are neglected	30–40	20–30

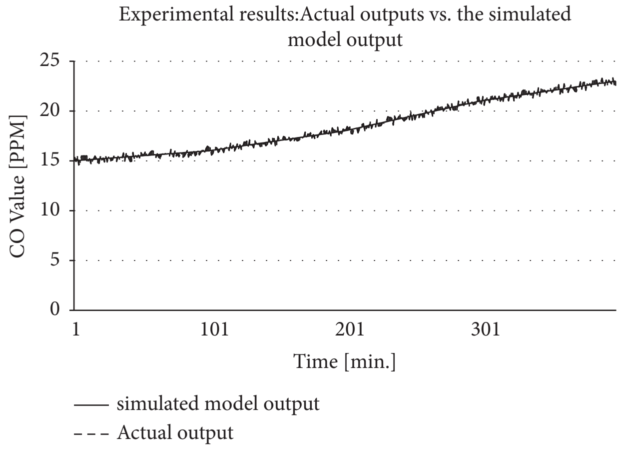

Figure 17: A comparison between Co actual outputs and the simulated model output.

is increased. The slopes of this increase are different in one-hour distance time. To begin with, this slope is one percent. In addition, the slope is two percent. Furthermore, it reaches to three percent. In conclusion, it reduces to two percent, again. It is concluded that the high traffic condition was carried out in samples 200–300 for one-hour duration. This figure shows that the simulated values precisely met the actual value throughout the simulation time. Nonetheless, the mean absolute error for these simulation results is found to be 1.38% which is acceptable. The experimental results show that the modeling of tunnel ventilation has a good performance in normal traffic condition.

6. Conclusion

In this paper, ventilation control system modeling and emergency response system design are presented for an intelligent transportation system. These two systems have a high priority in the design of an intelligent UAT. In order to validate the proposed ventilation model, three research works were performed; first the simulated data were evaluated for various conditions and the CO value waveforms were depicted. Second, the comparative work was performed with two closely related references so far. Finally, experimental results for actual data are illustrated for conclusion.

6.1. Achievement. The major achievement of the proposed model is to discover an adequate model for a tunnel ventilation system with faster response, low overshooting, and a lower settling time than existing methods so far. This achievement is concluded in Section 5.3. The proposed model is caused to raise security, reliability, controllability, and safety in the operation of tunnels. Another achievement of this paper is to lead an operator to make a correct decision in the operation of the tunnel in both normal and emergency conditions, avoiding any casualty of human beings in emergency conditions. Also, it reduces costs and increases reliability and safety in UATs. These achievements are used by SCADA developers and system engineers to implement them in the master control center as a pattern.

Thus, the proposed closed-loop ventilation control system with traffic intensity as the input signal and CO value as the output value are shown. The results conclude that the proposed ventilation system presents satisfactory performance under high traffic intensity. Moreover, this control system can decrease CO level from the higher value down to the desired value which is accepted by PIARC. In addition, there are no steady-state errors in the output CO value and fast response controlling is achieved. Considering various PI coefficients for this controller, the results show that little proportional coefficient variation ($kp = 0.01$) causes a small overshot value in the CO content which is a favor to all human beings. In this sense, the proposed method shows the accepted value for these parameters. The response time is less than 16.7 minutes, the overshot value is less than 33%, and the settling time is less than 35 minutes. At least, to demonstrate the superior performance of the proposed method, a comparison between CO actual outputs and the simulated model output is studied in the paper which ends up with an acceptable mean absolute error. This error value is 1.38% and it discovers that the proposed model has high adaptability with the actual tunnel ventilation system.

6.2. Limitations. In this paper, the impacts of natural wind velocity and the piston effects of vehicles in the tunnel are neglected, so these effects on the results are the main limitations in this manuscript. Meanwhile, any effects of the external weather conditions either in bad conditions or in normal conditions are overlooked.

6.3. Future Works. Based on the research on its peripheral subjects, the following subjects of future works can be proposed:

(i) Analysis of the effects of the shape of the tunnel on the tunnel ventilation system
(ii) Analysis of the effects of jet fan types on the tunnel ventilation system
(iii) Obtaining a method to optimize the location of jet fans and sensors on the tunnel ventilation system
(iv) Obtaining a method to optimize the number of jet fans and sensors on the tunnel ventilation system
(v) Implementing artificial intelligent methods for modeling of the tunnel ventilation system
(vi) The piston effects of vehicles in the tunnel
(vii) The natural wind velocity effects in the tunnel
(viii) Analysis of effects of the bad environmental conditions such as typhoons on the measurement systems and on the results

Nomenclature

List of Variables

T_i:	Integral coefficient of PI (proportional-integrator) controller
k_i:	Proportional coefficient of PI controller
T_j:	Time constant of the jet fan
k_j:	Numerator coefficient of the jet fan
T_t:	Time constant of the tunnel plant
k_t:	Numerator coefficient of the tunnel plant
T_s:	Time constant of the CO measurement system
k_s:	Numerator coefficient of the CO measurement system
T_v:	Time constant of the traffic system
k_v:	Numerator coefficient of the traffic system
$F_{JF}(S)$:	Laplace transfer function of the jet fan
$F_{TP}(S)$:	Laplace transfer function of the tunnel plant
$F_{CO}(S)$:	Laplace transfer function of the CO measurement system
$F_{Ts}(S)$:	Laplace transfer function of the traffic system.

Data Availability

The data used to support the findings of the study are included within the article.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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