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THE IMPORTANCE OF THE DATA TAKEN FROM THE NO, NO_2, AND CO SENSORS IN THE VENTILATION PROCESS IN THE RAILWAY TUNNELS

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ABSTRACT

In railway tunnels, ventilation is carried out to prevent NO, NO_2, and CO gas pollution caused by exhaust gases due to the diesel locomotives on the railway. Some ventilation calculations are used during ventilation. In these calculations, factors like the location and the structure of the tunnel and the pressure belts that may occur should be considered one by one. After these calculations, control scenarios are prepared based on the locations and dimensions of the ventilation equipment to be used. Programmable logic controllers (PLC) control these control scenarios. In this system, data is needed for the devices to work efficiently and correctly. These data are obtained in real-time through sensors. These are NO, NO_2, and CO sensors that measure toxic gases. The information received from the sensors provides the necessary information to start, continue, stop or switch to other scenarios. These sensors are needed to provide data required to operate jet fans and axial fans to ventilate the tunnels. This article describes the location of sensors and programmable logic controllers in the ventilation process in railway tunnels.

Keywords: Railway tunnels, NO and NO_2 sensors, CO sensors

1. INTRODUCTION

Today, there are specific emission standards to limit exhaust gas emissions. No matter how much it is desired to minimize exhaust gas emissions, it cannot be reduced to zero. The reason for this is that the engine technology working with fossil fuels cannot be abandoned entirely. Exhaust emissions of vehicles on highways and railways are limited to engines that comply with the standards specific to the vehicles themselves. However, additional precautions should be taken in railway tunnels. If these additional precautions are not taken, toxic gases such as CO, NO, and NO_2 accumulate in the air inside the tunnel. The reduction in the amount of oxygen in the air is harmful to human health. It also means that vehicle engines cannot get enough oxygen during fuel combustion, and efficiency decreases. Priority is for human health, and secondly, for vehicle health, ventilation is carried out in tunnels (road and railway) that are longer than a certain length. The transfer of the information from the placed NO, CO, and NO_2 sensors inside the tunnel to the automation system and the decision mechanism about the operation of the jet fan / axial fans used in the tunnel are the fundamentals and named as the ventilation process in tunnels. The critical design parameters used in the ventilation process in the tunnels, properties of the materials used, and calculations are given in the continuation of the article in the form of main headings. A sample flow chart of the ventilation system automation control is also provided to demonstrate the importance of sensors, which is the main point to be reached.

2. VENTILATION SYSTEM CALCULATION AND PRINCIPLES

This section will discuss ventilation system design criteria, design parameters and principles, and necessary calculations [1].

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2.1. Design Criteria

In ventilation system design, the first consideration is about environmental specifications. The system design is based on environmental specifications, salient features, and other vital data. These specifications can be listed as follows:

- Altitude
- Temperature
- Humidity
- Seismic Zone
- Strongest Wind
- Tunnel Height
- Tunnel Width

The purpose of tunnel ventilation is to supply required fresh air both in normal operation and event cases. In the normal case, the aim is to supply fresh air to reduce exhaust gases and particulate concentrations. On the other hand, in the event case, the aim is to send away the smoke and heat during a fire in the opposite direction of escape way.

In design, PIARC Standards are used during calculations. The jet fans that will be used should stand 400^{o} C at least 120 minutes due to the standards. The main following design standards, guidelines, and reference documents have been adopted for the current design are:

- NFPA 130: Standard for Fixed Guideway Transit and Passenger Rail Systems,
- NFPA 502: Standard for Road Tunnels, Bridges, and Other Limited Access Highways,
- PIARC- 1995 [2].

2.2. Ventilation Principles, Parameters and Calculations

2.2.1. Environmental conditions

The environmental conditions strictly affect the design. The design air temperature in the tunnel is the reference value that can vary according to the coordinates of the tunnel. The accepted value changes according to the region where the tunnel is located. The following equations can estimate the local static pressure and density at different altitudes:

$$p = p_0 \cdot e^{-\frac{gMh}{RT_0}} \tag{1}$$

$$\rho = \rho_0 \cdot e^{-\frac{gMh}{RT_0}} \tag{2}$$

where:
p_o: static pressure at sea level (101325 Pa)
p: local static pressure [Pa]
ρ_o: air density at sea level (1.2 kg/m^3)
ρ: local air density [kg/m^3]
h: altitude [m]
g: gravity acceleration (9.8m/s^2)
M: molar mass of air (0.029kg/mol)
R: universal gas constant (8.314 J/mol-k)
T_o: ambient temperature [K]

According to the above formulas, values can vary according to the coordinates and location of the tunnel.

2.2.2. Design parameters

The main design parameters and their purpose in the ventilation system can be summarized with the following table:

Table 1. Design parameters

Parameter	Purpose
Fire heat release rate	Critical velocity calculation
Drag coefficient	Pressure loss
Wind speed	Wind effect calculations
Local air density	Pressure loss calculations
Smoke density in the tunnel	Pressure loss calculations
Air velocity in the tunnel during emergency conditions	Critical velocity
Length of tunnel affected by fire	Chimney effect
Pressure drop coefficient for entry and exit	Pressure loss calculations
Friction factor for tunnel concrete wall & floors	Pressure loss calculations
No. of vehicles at a time in the tunnel	Pressure loss calculations
Jet fan installation coefficient	Effective thrust calculations
Froude Number factor	Critical velocity calculations
The temperature of the approach of the air	Critical velocity calculations

In ventilation calculations, we need the critical speed value according to the fire load. Critical velocity is the lowest air velocity value we need to prevent the smoke generated during a fire from moving in the opposite direction. This value depends on the parameters such as tunnel height, cross-sectional area, slope, air temperature, air density, and fire load.

Pressure loss also should be taken into consideration. There will be pressure losses in the tunnels due to friction, the chimney effect, the wind blowing against the portal, and the portal and the train standing inside the tunnel. Depending on these pressure losses, the thrust required for pushing the smoke will be found.

Wind effect is another parameter in calculations. Winds coming from tunnel portals will create a resistance for the tunnel and cause pressure loss. This situation is called the wind effect.

Chimney effect can be described as a resemblance since the train lines will act as a chimney as a tube, pressure loss will occur. This pressure loss is called the pressure loss due to the chimney effect.

Under normal operating condition, there is no design standard governing rail tunnel environment. In general, the final design has adopted the environment criteria by PIARC guidelines as:

- $CO < 20$ ppm,
- $K = 0.003\ m^{-1}$,
- $NO_2 <= 1.0$ ppm

where CO, K and NO_2 represent the CO concentration, extinction coefficient (visibility), and NO concentration in the tunnel, respectively (ppm: parts per million). The above criteria are for maintenance work in tunnel. It is a scenario similar to congested traffic when a train with open windows is forced to stop in the tunnel [3].

2.2.3. Calculations

In case of fire at any point of the tunnel, it is necessary to quickly evacuate the dense smoke consisting of (CO, NO, and NO_2) gases out of the tunnel. In order to do this, the number of the equipment used in ventilation systems and their capacities must be of sufficient size. Here calculations are made accordingly, according to the emergency mode.

2.2.3.1. ***Pressure drops***

Pressure drops due to friction with the tube concrete walls and floor (friction coefficient = 0.025 for plain concrete) can be calculated by the equation 3:

$$\Delta P_1 = \frac{\lambda L v^2 \rho}{2 D_H} \tag{3}$$

where:
λ: wall friction coefficient for tube
L: the length of the tube
V: the air velocity
ρ: local air density
D_H: hydraulic diameter of the tube

The chimney effect (buoyancy effect) can be calculated by equation 4:

$$\Delta P_2 = \left(\rho - \rho_{smoke}\right) dgL \tag{4}$$

where:
ρ: local air density
ρ_{smoke}: smoke density
d: average tunnel gradient
g: gravity acceleration
L: the length of the tube

Because of the fire situation, ΔP_{stack}, the pressure drop for the fire itself, must be added to the ΔP_2, the pressure drop calculated in equation 4. In fire case, the equation is updated as below:

$$\sum \Delta P_2 = \Delta P_2 + \Delta P_{stack} \tag{5}$$

Pressure loss at the portals can be calculated by equation 6:

$$\Delta P_3 = \left(1 + \xi\right) \frac{\rho v^2}{2} \tag{6}$$

where:
ξ: pressure drop co-efficient to be 0.6 for the entrance portal and 1 for the exit portal
ρ_{smoke}: smoke density
v: the tunnel air velocity

Pressure drop due to wind blowing against the portal can be calculated by equation 7:

$$\Delta P_4 = \frac{\rho \left(w \sin(x)\right)^2}{2} \tag{7}$$

where:
ρ: local air density
w: wind speed
x: wind angle (wind angle is usually taken as 90 degrees)
Pressure drop due to the vehicles stopping inside the tunnel can be taken into consideration by using equation 8 as follows:

$$\Delta P_5 = \rho \left(\frac{C_x S_v}{S_T} \right) \left(\frac{(v_v - v_a)^2}{2} \right) N \quad (8)$$

where:
C_x: vehicle drag coefficient
Sv: vehicle cross-section area
S_T: tunnel cross-section area
ρ: local air density
v_a: the tunnel air velocity
v_v : vehicle velocity
N: the number of vehicles

Therefore, the total pressure drop can be calculated as a sum of the equations given between equations 3 and 8, due to the different scenarios. Thus, the total pressure drop is given in equation 9.

$$\sum \Delta P = \Delta P_1 + \sum \Delta P_2 + \Delta P_3 + \Delta P_4 + \Delta P_5 \quad (9)$$

2.2.3.2. ***Thrust***

The nominal thrust of the jet fan, which is obtained from the test bench shall not be the effective one to be taken into account inside the tunnel. If the total pressure drop (Pa) is multiplied by the tunnel cross-section (m^2), the thrust can be found.

2.2.3.3. ***Number of jet fans***

After calculating the thrust, the number of the required jet fans is an essential and critical design issue in tunnel ventilation.

There will be some losses in accordance with the following main parameters summed up, and the values of these parameters are considered based on PIARC 1995. We may consider the efficiencies as follows:

- $\eta 1$ = jet fan performance or efficiency
- $\eta 2$ = wall friction (installation efficiency)
- $\eta 3$ = influence between jet fans (efficiency of the total system)

The thrust found is divided by the effective thrust of the jet fan, so the number of jet fans needed in the tunnel is found. The number of jet fans required can be found by dividing the thrust by the multiplication of the jet fan flow, jet speed, and the overall efficiency. Therefore, the number of jet fans needed is equal to = Thrust / (Jet fan flow *x* jet-speed *x* ρ local *x* $\eta 1$ *x* $\eta 2$ *x* $\eta 3$).

For the normal operation case, the piston effect of the moving train is sufficient to move away the pollutants out of the tunnel. In case that the CO level is above the limit and/or the visibility is poor; suitable numbers of jet fans for the needed locations of the tunnel can be activated until the air quality is proven to improve to the safe limits.

3. TUNNEL SENSOR PRINCIPLES

In this section, the details of the sensors in the tunnel are discussed. The design of the system is made based on environmental specifications, salient features and other key data such as altitude, temperature, humidity, seismic zone, the strongest wind speed, and tunnel dimensions [4].

In this ventilation system normal operating mode, the measured air quality in the tunnels shall be the input of the control system. From the tunnel, dust particle concentration, as well as the direction and the velocity of the air, train velocity shall be available. The CO, NO, and NO_2 values from the tunnel shall be compared, and only the highest value of the tunnel shall be used as an input to the ventilation control system. Similarly, the higher of the light extinction values of the tunnel shall be used as an input to the control system. This situation shall be necessary to compare the carbon monoxide concentration with the dust particle concentration.

If the carbon monoxide and the light extinction values both fall within the threshold values of one of the same ventilation step, then no other switch selection shall be made; just the needed switch selection has to be executed. If they fall within different switching thresholds, the higher ventilation step shall be selected. The design limit table is as follows:

Table 2. Design limits

Emission	Normal Operation	Maintenance Operation
CO	50 ppm	30 ppm
NO	25 ppm	25 ppm
NO_2	5 ppm	4 ppm
Particle	0.007 m^{-1}	0.003m^{-1}

The normal operation is the situation when there is regular traffic in the tunnel, and the number of the people inside is acceptable. On the other hand, in maintenance operation case, when there is maintenance in the tunnel (it may be electrical, mechanical, or constructional maintenance), and the number of people in the tunnel will increase. Therefore, the values taken from the sensors are kept at a lower level to operate the ventilation process safely. Thus, the toxic gas in the tunnel is to be reduced for human health. For these cases, the maintenance operation scenario has to be run.

Sensor types mainly used in railway tunnels are CO, NO, and NO_2 sensors. Apart from the above sensors, there are visibility and air velocity & wind direction sensors. A visibility sensor is used to measure the visibility distance of vehicles and pedestrians inside the tunnel. They enable the ventilation elements to work in cases such as smoke density, fog density. Air velocity and wind direction sensors are used to determine the direction of rotation of ventilation equipment such as a jet fan or an axial fan according to the wind direction and speed.

CO (carbon monoxide) and PM (opacity) detectors are sensors for simultaneous measurement of CO, and visibility has been provided for the tunnels. The measured values are used to control the ventilation system.

NO and NO_2 sensors are for accurately monitoring the limit values of NO and NO_2 have been provided for the tunnels. These measured values are used to control the ventilation system. The functioning criteria for NO and NO_2 gases are based on light absorption with different wavelengths to varying extents. Plotting the intensity of the light beamed through the gas as a function of the wavelength gives a characteristic spectrum for each gas component, which more or less represents the fingerprints of the gases.

4. TUNNEL AUTOMATION SYSTEM PRINCIPLES AND GENERAL PROPERTIES

Automation systems generally will provide information from desired equipment in the field and realize pre-determined scenarios based on the information received. Automatic processes will provide redundant PLCs and remote I/Os. All PLCs have permanent communication with each other. The data transmission between the PLCs and the remote I/O units will be communicated with redundant PLC over the fiber optic cable ring. Communication protocol will be OPC (Open Platform Communications) protocol between SCADA system and automation system. Modbus TCP or Modbus RTU protocol will be between PLC with VFD, soft starter, etc. It will use digital and analog input/output between PLC power system and the ventilation system.

4.1. Programmable Logic Controller (PLC)

PLC configurations will be redundant and completely modular. The main processor module (CPU module) at the controller level will be in a hot standby configuration. One of the processor modules acts as a primary controller and the other acts as the hot standby module and always be ready to take control if something is wrong with the primary CPU module. Automation system design architecture can be seen in Figure 1 [5].

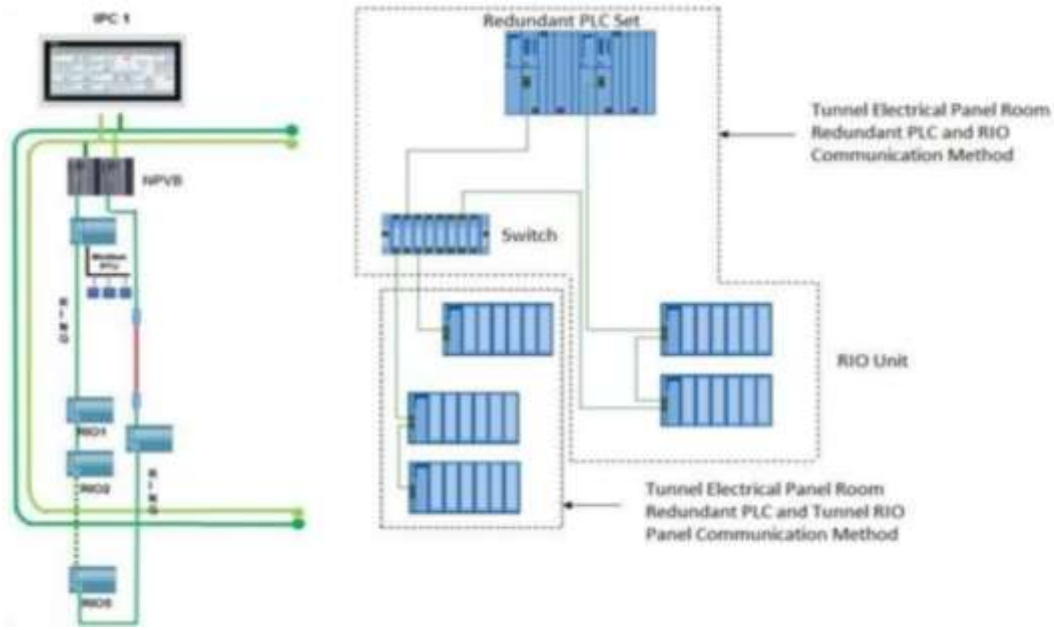

Figure 1. Automation System Design Architecture

4.2. Tunnel Automation System Principles and General Properties

In order to make the PLC architecture used in a railway tunnel more efficient in today's conditions, PLCs with the following features are generally used.

The changeover from the primary to the hot standby controller will be bumpless must not affect the controlled process. The hot standby system will detect a switchover causal event within 15 ms. the time to complete a switchover time will be below 15 ms and will be bumpless. After the switchover, the former hot standby controller becomes the primary. The synchronizing between the primary and hot standby controllers will utilize a dedicated synch link port at the CPU module with 1 Gbps transmission speed and shall be available in FO cable or cat-6 twister pair copper cable.

Controllers will have the ability to change the configuration on the running without stopping the process. The user will be able to change the configuration online while the system is running normally without stopping the process. The CPU module will have LED display for CPU diagnostic and a status indicator for the first check of the CPU. Power supply redundancy of various ranges will be possible. Power supply module with advanced diagnostic for predictive maintenance and the power supply module switchover. The main processor module will have an embedded web server consisting of diagnostics, status, and health data.

The embedded web server will have rack viewer features. The rack viewer is the feature that shows up the ball hardware modules configuration in the control system and every healthy module's status.

The web server shall be accessible by only key in the IP address of the main processor module at the internet browser program. The software can integrate a controller simulator that can test the application program for the controller without connecting to the CPU module processor. The functions provided by the debugging tools are available for debugging the master, fast and auxiliary tasks. Timestamping will be able to be by configuration without extra programming efforts over PLC or SCADA system.

5. FLOW CHART OF THE TUNNEL VENTILATION SYSTEM

The information received from the sensors is processed by analog data (4-20 mA or 0-10 VDC) with PLC. It sends the command to the fans to operate according to the region of gas density. A sample algorithm of the program written in the PLC related to this subject is given in a flow chart in Figure 2.

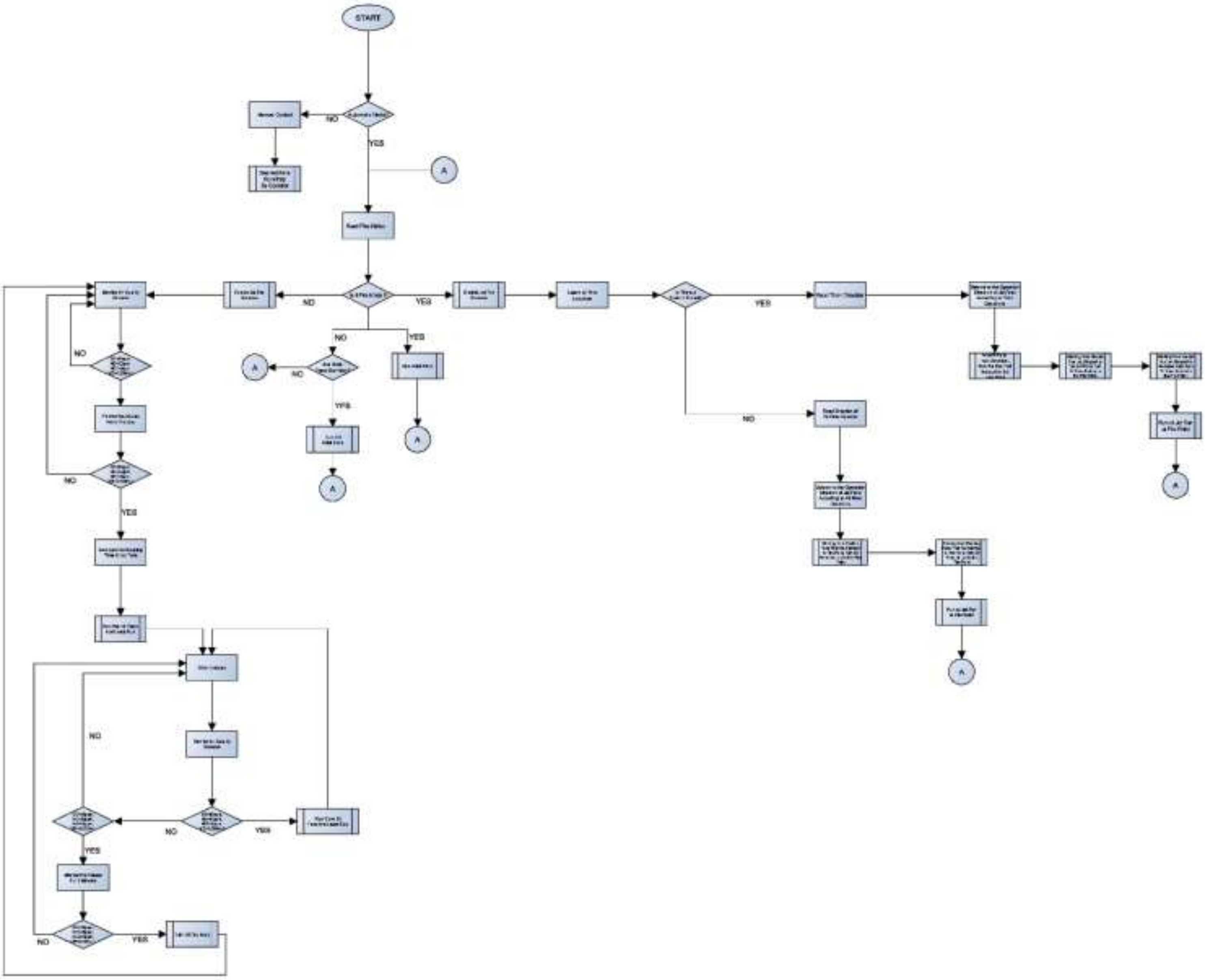

Figure 2. Sample flowchart for tunnel ventilation system

6. CONCLUSION

In summary, to prevent air pollution in railway tunnels, selection, and calculations of ventilation elements, the purpose of use of the sensors and their importance in the process, and finally, the programmable logic controllers that provide the bridge between the ventilation system equipment and the sensors were mentioned. A ventilation system is installed to eliminate the harmful effects of air pollution in the tunnels on human health and vehicle efficiency. The importance of sensor mechanisms, which are a part of this ventilation system, measure the pollution in the environment and decide the start and end of the whole ventilation process in the railway tunnels.

CONFLICT OF INTEREST

The authors stated that there are no conflicts of interest regarding the publication of this article.

REFERENCES

[1] Northern Railway, Udhampur-Srinagar-Baramulla- Rail Line Project, Tunnel T-14&T-15 + T-40/41, Ventilation Design Report, 2021.

[2] PIARC Committee on Road Tunnel Operation (C-5), Tunnel Classification, 1995.

[3] PIARC Committee on Road Tunnel Operation (C-5), Route/Roads, PIARC Proposal on Design Criteria for Resistance to Fire for Road Tunnel Structures, 2003.

[4] Northern Railway, Udhampur-Srinagar-Baramulla- Rail Line Project, Tunnel T-14&T-15 + T-40/41, Tunnel Sensors Design Report, 2021.

[5] Udhampur Srinagar Baramulla Rail Link Project, Automation System Design Report, 2020.