ROAD TUNNEL TEMPERATURE MONITORING SYSTEM USING A SIMULATION MODEL

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ABSTRACT

This paper is concerned with a road tunnel temperature monitoring system which detects incident such as fire, congestion and stationary vehicle by capturing the temperature rise which originates in *only* the incident. The system captures the rise comparing the temperature measured by a linear temperature sensor cable and the value predicted by a temperature simulator built in the monitoring system. Successful fire detection will be presented using the temperature data recorded at a real tunnel fire test, thereby proving the proposed road tunnel temperature monitoring system works effectively. Congestion and stationary vehicle detection are also sketched. The merits expected from a simulator in the monitoring system, which is rarely seen in the road tunnel industry, are also presented.

Keywords: linear temperature sensor cable, temperature monitoring, temperature simulator, fire detection, automated incident detection

1 INTRODUCTION

Monitoring the road tunnel is indispensable to maintain the tunnel environment in good shape. Traditionally improving tunnel air quality was the primary issue due to the exhausted gas of vehicles. Nowadays, however, technologies have advanced substantially to solve the air pollution issue by introduction of the clean-burned diesel, hybrid, and electric vehicles. As a result, tunnel air quality is improved significantly. On the other hand, tunnel air temperature is becoming a new problem. Urban city tunnels are reported to face high temperature issue due to underground-built, long-distance and complex structure of expressways. During the congestion hours in morning and evening urban tunnels experience temperature rise. In some tunnels it gets as hot as about 40 °C in summer, and motor bike riders will be affected a lot if they are in congested traffic [Matsuzaki and *et al.*, 2019].

Road tunnels always experience temperature change by its nature, causing various problems in hot summer and even in cold winter. The most dangerous situation in tunnel temperature rises is a fire. It is very important to detect the fire and identify the location accurately when and where a fire occurs in a long-distance tunnel. To detect and respond to such incident, constant monitoring of tunnel temperature plays a critical role. With these in background an operator-friendly prototype of tunnel temperature monitoring system was developed. The present paper will describe the concept, outline and verification of the system, which has the unique feature to detect and diagnose various incidents such as fire, congestion and stationary vehicle by comparing a temperature profile measured by a linear temperature sensor cable ("sensor cable") and the one predicted by a built-in simulator.

2 OUTLINE OF TEMPERATURE MONITORING SYSTEM

2.1 Objective of the system

The objective of the proposed system is to use continuous temperature monitoring to detect incident such as fire, congestion or stationary vehicles. However, providing only measured temperature profile will result in a big burden to operators. The proposed system detects symptom of an incident automatically and provide operators with a useful and effective information to help them to make a correct decision.

2.2 Outline of the system

Figure 1 illustrates a sample screen shot of the monitoring system under normal operation. All data that include visibility index ("VI"), carbon monoxide ("CO"), airflow velocity ("AV"), jet-fan output, traffic, and temperature profile are displayed and monitored in one screen. As for temperature data, both a profile measured by sensor cable (shown as Graph A) and a difference profile compared with the temperature projected by a built-in simulator (shown as Graph B) are displayed. Sensor cable measures the temperature at constant interval (e.g. 5m). A heat map which illustrates temporal behavior of the temperature difference in shade of color depending on its amplitude is also displayed (shown as Graph C) on the screen so that temperature evolution is captured intuitionally.

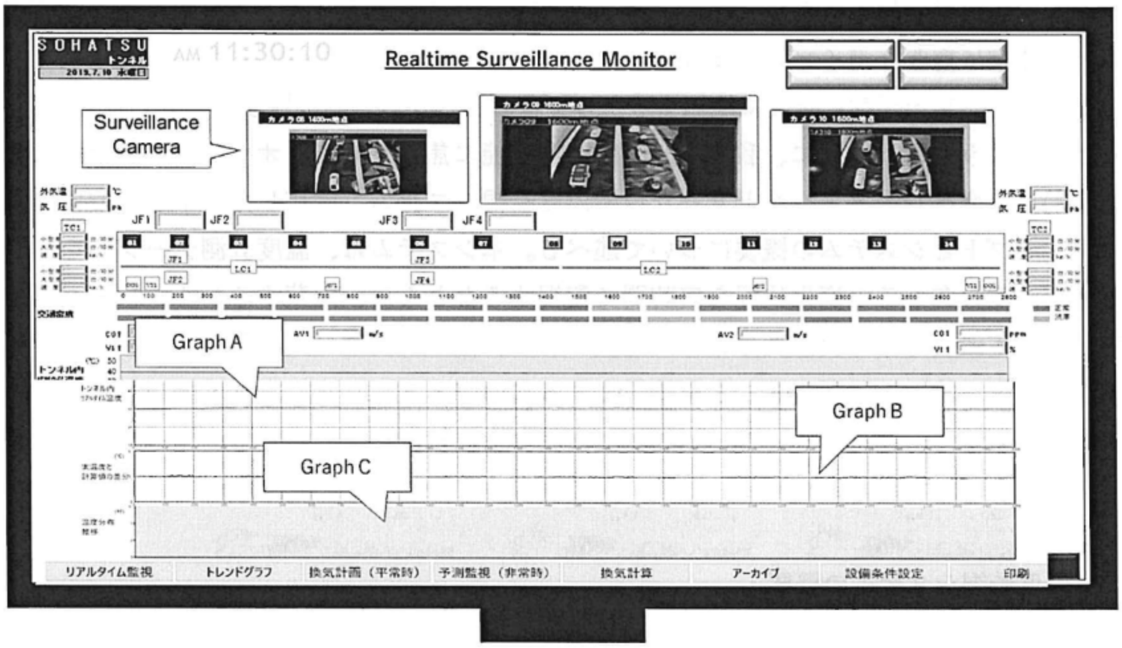

Figure 1: Screen display of the temperature monitoring system at normal operation

3 SYSTEM CONFIGURATION

The proposed temperature monitoring system is configured as shown in **Figure 2**. The system is built on a personal computer ("PC"). Measured data of sensors and ventilation equipment are all collected via data acquisition function periodically, every second for example, in programmable logic controller ("PLC") and stored in the Data Base temporarily. A simulator built in the system predicts the temperature profile at constant time interval, every second in this paper. In parallel incident detection function analyzes the difference between measured temperature in the Data Base and predicted temperature. The incident detection is conducted synchronizing to data acquisition cycle. In case an incident has been detected, alarm of the incident and location are stored in the Data Base.

The screen display function updates the screen in real time periodically, e.g. every second, with the measured temperature data stored in the Data Base. If an alarm indicating an incident is ON, the display function highlights the alarm on the screen. The screen display function controls the selection of the video cameras to be displayed on screen. When an incident like a fire is detected, the system switches the camera to the one which is the nearest to the location of the incident based on the data stored in the Data Base. The screen display function needs to be compatible with the 4K display.

As there are thermal cameras which come with fire detection function, a fire can be detected by thermal camera. Fire detections with temperature rise and thermal image are complementary with each other in a way that the final conclusion would be made when both of fire detections by the linear temperature sensor cable and the thermal camera activate an alarm at the same fire. Reliability of fire detection will be improved by the use of both data.

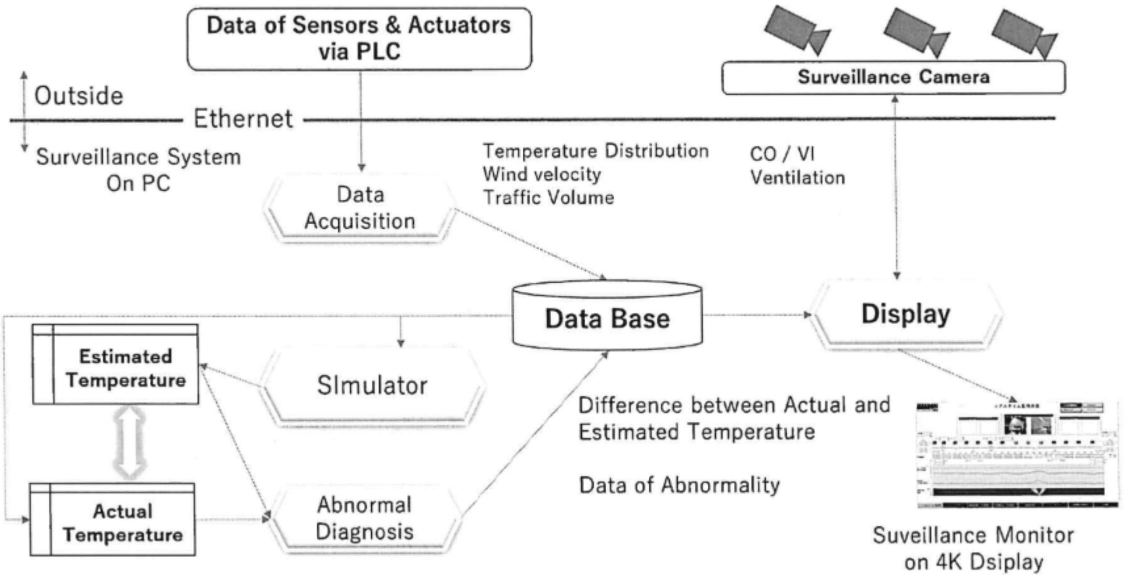

Figure 2: Configuration of the temperature monitoring system

4 TEMPERATURE SIMULATOR AND INCIDENT DETECTION

4.1 Data acquisition

Field data such as tunnel temperature profile, incoming traffic, VI, CO, AV and jet-fan output in tunnel are collected in a PLC at constant time interval, and updated in the Data Base. Individual system functions conduct each calculation by referring to the data in the Data Base.

4.2 Temperature simulator

As is shown in **Figure 3**, the simulator consists of three components: traffic, velocity and temperature distribution simulator.

(a) Traffic simulator: predicts vehicle distribution in the tunnel at every second, based on an input of incoming traffic volume at entrance portals, using a fluid macro traffic model.

(b) Velocity simulator: calculates forecasted longitudinal airflow velocity in the tunnel at every second, based on the predicted vehicle distribution and ventilation fan outputs.

(c) Temperature distribution simulator: forecasts temperature profile in the tunnel at every second based on predicted vehicle distribution and airflow velocity, both of which are simulated by the above two simulators (a) and (b). The basic equation of the temperature distribution prediction used in the simulator is shown in the equation (1).

$$\frac{\partial T}{\partial t} + \frac{\partial (TV_r)}{\partial x} = D_K \frac{\partial^2 T}{\partial x^2} + \frac{\xi_T}{C_p} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where T: absolute temperature [K], t: time [s], x: distance [m]

V_r: average flow velocity [m/s], D_k: turbulence thermal diffusion coefficient [m^2/s]

ξ_T: total heat release [J/s m^3], C_p: specific heat capacity [J/m^3 K]

The simulator calculates the temperature distribution $\widehat{T_j}$(k) by solving the discrete model of the equation (1).

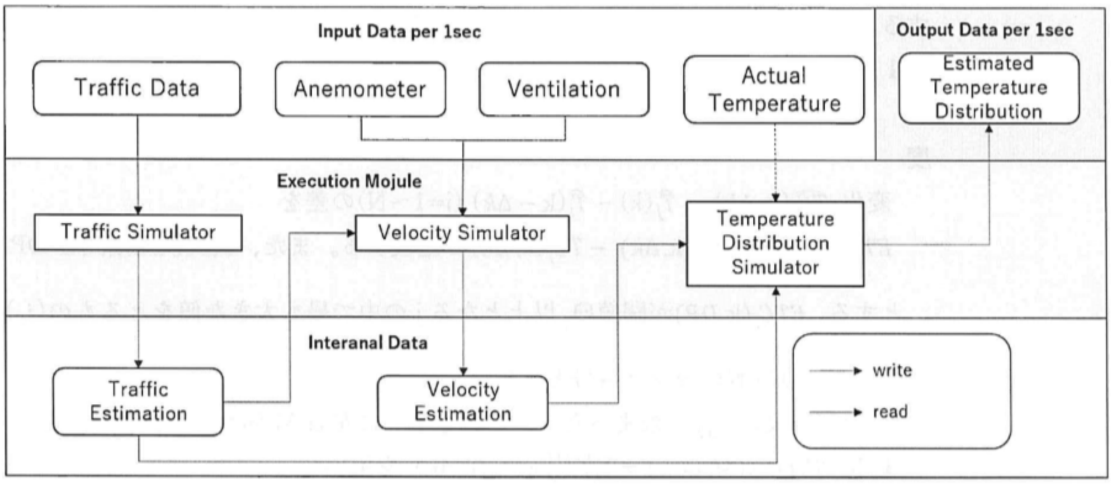

Figure 3: Internal structure of the simulator

4.3 Incident detection

Incident detection function is structured as shown in **Figure 4.** Every 10 seconds, which are the data acquisition cycle of the sensor cable, the difference of measured temperature distribution and predicted one is tested to see if non-zero value is observed. If non-zero value is observed, it would imply a possible incident assuming no sensor failure. The difference will be written and updated in the Data base. Incident detection of fire, congestion and stationary vehicle is conducted in parallel as shown in **Figure 4**.

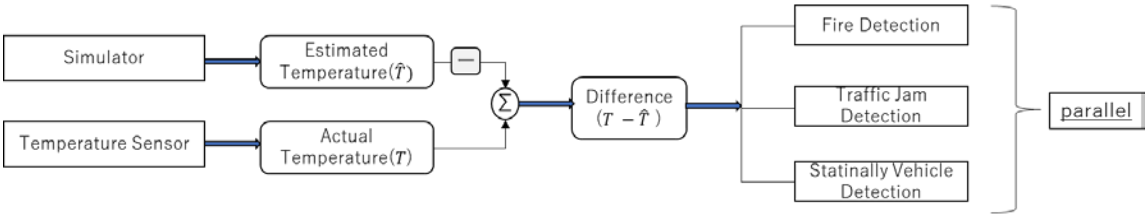

Figure 4: Process of the incident detection

(1) Fire detection

Fire detection is conducted by modifying the existing method [Nakahori and *et al.*, 2018], which used *only* measured temperature profile to capture a change in the historical trend of the temperature rise. The ordinary temperature, however, fluctuates depending on out-tunnel temperature rise or fall, and in-tunnel temperature rise or fall due to traffic change. Having considered the ordinary change, the fire detection method has been revised to take into account the difference of the rate of change in not only measured temperature but also simulated one. By this revised method, the ordinary temperature fluctuation is *completely* filtered out, thus able to improve the accuracy of fire detection.

Let measured temperature of the sensor *j* at time *k* be $T_j(k)$, corresponding simulated one $\widehat{T}_j(k)$ and *N* the total number of sensors. The revised fire detection method is described as follows.

<1> Temporary estimate of fire location: Let the measured temperature change in Δk second be:

$$TC_j\ (\mathrm{k}, \Delta k) = T_j(\mathrm{k}) - T_j(k - \Delta k)\quad (\mathrm{j}=1, \ldots, \mathrm{N})$$

Let the simulated temperature change in Δk second be:

$$\widehat{TC}_j\ (\mathrm{k}, \Delta k) = \hat{T}_j(\mathrm{k}) - \hat{T}_j(k - \Delta k)\quad (\mathrm{j}=1, \ldots, \mathrm{N})$$

The difference of these two changes is defined as:

$$ETC_j(\mathrm{k}, \Delta k) = TC_j\ (k, \Delta k)\ - \widehat{TC}_j(\mathrm{k}, \Delta k)$$

Suppose the fire detection time be *DP* second. Then a temporary estimate of fire location j_F be defined as the sensor number *j* which shows the largest *ETCj (k, DP)* among those that exceeds the threshold Θ_F.

<2> Selection of fire location hypothesis: suppose that the temporary estimate of fire location j_F is selected. Then the spatial integration of $ETC_j(\mathrm{k}, \Delta k)$ of *j=-M* to *j=M* in the equation (2) is calculated.

$$SETC_{\Delta k}(M, j_F, k) = \sum_{j_F-M}^{j_F+M} ETC_j(k, \Delta k) \ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

If the following two are satisfied at the sensor j_F, then it is accepted as a fire location hypothesis.

$$SETC_{SP}(M, j_F, k) > \Theta_{SP}$$

$$SETC_{DP}(M, j_F, k) > \Theta_{DP}$$

Where Θ_{SP} is the threshold for $SETC_{SP}$, *SP* is the data acquisition interval (usually 10 sec), Θ_{DP} is the threshold for $SETC_{DP}$ and *DP* is the fire detection time (usually 30 s).

<3> Testing hypothesis: if the following four tests all become TRUE, then the fire hypothesis is accepted and fire alarm will be issued. Otherwise the hypothesis is rejected as FALSE and no alarm will be issued.

[Test-1] Evaluation of the ratio of temperature rise at the fire location j_F against temperature rise spatial integration in *DP* second.

$$E_v(1) = \frac{ETC_{j_F}(k, DP)}{SETC_{DP}(M, j_F, k)} \geq \Theta(1)$$

[Test-2] Evaluation of the ratio of temperature rise of the fire location j_F and its two neighbors against temperature rise spatial integration in *DP* second.

$$E_v(2) = \frac{SETC_{DP}(1, j_F, k)}{SETC_{DP}(M, j_F, k)} \geq \Theta(2)$$

[Test-3] Evaluation of the ratio of temperature rise spatial integration in *SP* second against temperature rise integration in *DP* second.

$$E_v(3) = \frac{SETC_{SP}(M, j_F, k-SP)}{SETC_{DP}(M, j_F, k)} \geq \Theta(3)$$

[Test-4] Evaluation of the ration of temperature rise spatial integration in *SP* second against temperature rise spatial integration in *DP* second.

$$E_v(4) = \frac{SETC_{SP}(M, j_F, k)}{SETC_{DP}(M, j_F, k)} \geq \Theta(4)$$

The prototype system was designed with *SP*=10 second, *DP*=30 second, *M*=5, Θ_f=0.3, Θ_{SP}=0.5, Θ_{DP}=1.1, Θ(1)=0.28, Θ(2)=0.5, Θ(3)=0.1 and Θ(4)=0.8.

(2) Congestion detection

The temperature rise caused by congestion is usually smaller than fire. The fire detection with the threshold value Θ_F will result in no alarm. A smaller threshold Θ_{TJ} ($<<\Theta_F$) can be selected for congestion detection. The average of the temperature difference $\Delta T_j(k) = T_j(k) - \hat{T}_j(k)$ over a certain period of time is compared with Θ_{TJ}, and congestion can be detected if $\Delta T_j(k)$ exceeds Θ_{TJ} at preset N_{TJ} locations. N_{TJ} is usually a large number (a few hundreds).

(3) Stationary vehicle detection

Suppose a situation that a vehicle is stationary at an emergency parking lot. The actual traffic in the lanes do not deviate from the simulated one. The predicted temperature profile would match the measured value except the location of the stationary vehicle. The temperature rises locally like fire but the degree of the rise would be much smaller than fire. The threshold value Θ_{SV} can be set for the stationary vehicle detection in a way that detection is made when the average temperature difference $\Delta T_j(k) = T_j(k) - \hat{T}_j(k)$ over a certain period of time exceeds Θ_{SV} at least Nsv locations. The smaller the incident to be detected, the greater the time interval to be used for assessment to avoid false alarm.

5 VERIFICATION

Fire detection was verified by applying the temperature data which were actually measured by a sensor cable and recorded at a real tunnel fire test. **Figure 5** is a screen shot displayed by the system when 30 seconds passed after fire breakout. Graph A shows the measured temperature profile, Graph B the difference profile of measured and predicted temperature, and Graph C the evolution of the difference respectively. A plate fire test data of 1 m^2 and 12 liters gasoline was applied to the fire detection method in section 4.3. The method resulted in acceptance of the fire hypothesis tests within 30 seconds, and a fire alarm and fire location are sent to the displaying subsystem. An alarm at the top-right of the screen turns ON, and camera images are automatically switched to the camera nearest to the fire location. Operators are advised of the fire alarm, location and camera image promptly, and they are supported to make the right decision in dealing with the fire emergency.

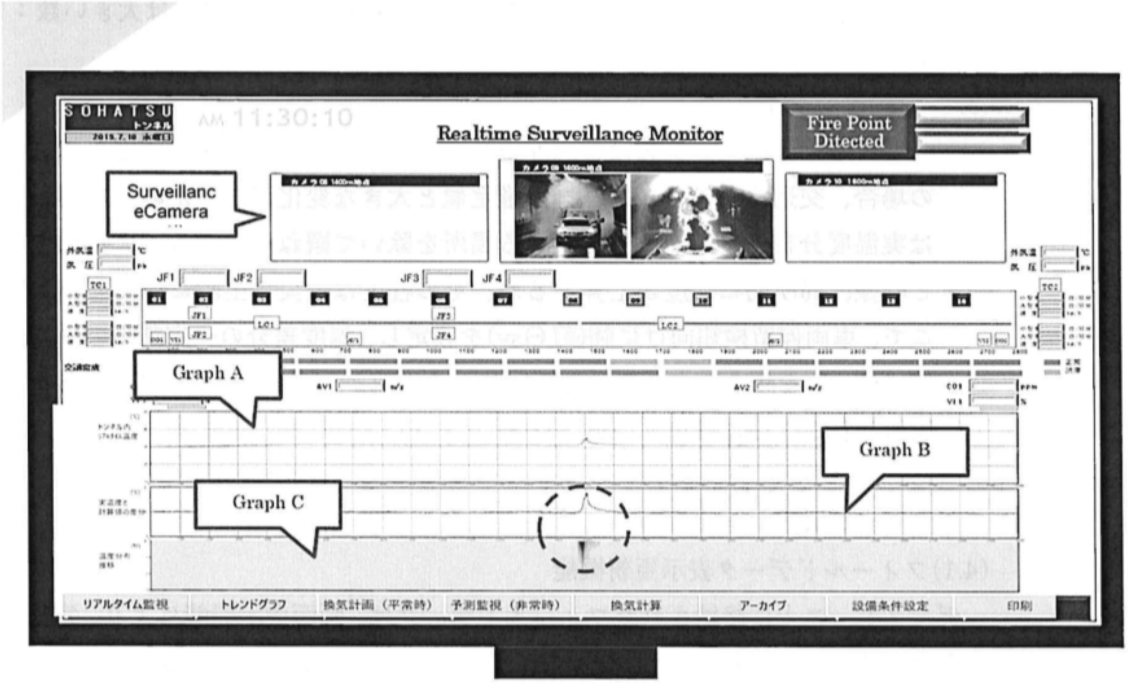

Figure 5: Screen display of the temperature monitoring system after fire detection

6 MERITS OF A SIMULATOR IN MONITORING SYSTEM

There are several merits of a simulator when implemented in the monitoring system.

6.1 Sensor failure detection

Suppose a simulator with standard tunnel sensors such as TC, AV, VI, and CO meters in addition to the temperature sensor cable of the present paper. The simulator can predict the value of those sensors and compare it with the measured value of the corresponding sensors. If the difference is large enough ($> 3\sigma$: the standard deviation) with a particular sensor, then a failure could be concluded in the sensor [Nakahori and *et al.*, 2012].

6.2 Prediction of future evolution

The temperature simulator of this paper can be advanced to the one which has a model of a fire scale, growth and emergency operations such as zero-flow control. Once fire is detected by the proposed method in this paper and fire scale by the published method [Nakahori and *et al.*, 2014], the advanced simulator could predict the fire growth and study an effect of various emergency operations over a certain time period in the future, for example over 10 minutes. Operators would be advised of the simulation results which provide various outcomes corresponding to individual scenarios. They would be able to select the best operational option among the studies.

7 CONCLUSIONS

The present paper has proposed a prototype of the tunnel monitoring system which focuses on the tunnel temperature. The system monitors the temperature profile measured by a linear temperature sensor cable, and conducts incident detection such as fire, congestion and stationary vehicle by comparing the measured temperature profile with the one predicted by the temperature simulator. In the monitoring system the temperature simulator plays a central role in providing useful information to operators. The system has been verified for fire detection by using the temperature data recorded at a real tunnel fire test. It has been confirmed that a fire is detected correctly and timely, and relevant information before and after fire breakout is provided to operators effectively in conjunction with a thermal/optical camera. Other potential benefits of a simulator in the monitoring system were discussed as a future research topic. The tuning of parameters in the simulator in the proposed temperature monitoring system will be the next challenge moving forward.

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