SENSOR FAILURE DETECTION IN ROAD TUNNEL VENTILATION

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ABSTRACT

Tunnel sensors measuring traffic flow, air velocity, visibility index, carbon monoxide and nitrogen dioxide are widely installed and used in road tunnels for ventilation control. If a sensor malfunctions, it can compromise reliability, especially in cases of *automatic* control. This paper proposes a method of detecting sensor failure by comparing measured and predicted values of air velocities and pollution concentrations in longitudinally ventilated tunnels. The detection method uses statistical comparisons of actual measurements and theoretical estimates of air velocities and pollution concentrations based on the evolving traffic conditions and assumed vehicle emission characteristics. The proposed method is illustrated using data collected in an actual tunnel.

Key words: sensor failure detection, longitudinal ventilation

NOMENCLATURE

A_{TL}, A_{TS}	: effective resistance area of large(small) vehicles	[m^2]
A_R	: cross section of tunnel	[m^2]
C_k	: pollution concentration in calculation box k	[g/kg-air]
$\dot{C}_k$	: rate of change of C_k	[g/kg-air/sec]
$F_J(t)$	: fan thrust at time t	[N]
$F_P(t)$	: natural ventilation force at time t	[N]
$F_R(t)$	: tunnel resistance force at time t	[N]
$F_T(t)$	: piston ventilation force at time t	[N]
N_{UL},N_{US}	: number of large(small) vehicles, up-bound lane	[veh./km]
N_{DL},N_{DS}	: number of large(small) vehicles, down-bound lane	[veh./km]
$V_R(t)$	: longitudinal air velocity at time t	[m/s]
$V_T(t,i)$	: i-th vehicle speed at time t	[m/s]
$\dot{V}_T(t,i)$	: i-th vehicle acceleration at time t	[m/s^2]
k	: calculation box number	
L	: tunnel length	[m]
t	: time coordinate	[s]
t_d	: total response delay time combining driver and vehicle	[s]
x	: distance coordinate (longitudinal)	[m]
α	: constant sensitivity factor	
μ_L, μ_S	: pollution gas emission by large(small) vehicles	[g/veh]
$\mu_k(t)$	: local pollution source rate in box k at time t	[m.g/kg-air/sec]
ρ	: air density	[kg/m^3]
σ	: standard deviation	

1. INTRODUCTION

Most road tunnels in Japan are single tube and two-way traffic. Longitudinal ventilation using jet-fans is the standard ventilation scheme in these tunnels, more than three hundred (300) of which are longer than 1,000m. Air velocity ("AV"), visibility index ("VI"), carbon monoxide ("CO") and nitrogen dioxide ("NO_2") sensors are installed as standard and data from them (especially VI sensors) are used in the automatic control of jet-fans. Clearly, the effectiveness of the control is strongly dependent upon the information received from the sensors and yet there will be occasions when this information is inaccurate. It is therefore desirable to have a reliable method of detecting sensor malfunction.

The authors have recently developed a new automatic control method called Feed-forward Cascaded feedback Ventilation Control ("FCVC") (Nakahori *et al*, 2010, 2011). This system requires the measurement of traffic volumes ("TC") in addition to air velocity and pollution and, in addition to greatly improving the reliability of control, it has the spin-off benefit of enabling a powerful method of detecting sensor failure. In a nutshell, the method works by continually assessing the self-consistency of the information received from the various types of sensor (traffic, air-velocity, pollution). The process is described in detail in the following sections and its effectiveness is then confirmed by the use of data from an actual tunnel. It includes the following fundamental steps:

(1) Using data from the traffic counter(s) ("TC") together with expected values of resistance parameters and exhaust emission rates, calculate theoretical estimates of the air velocity and pollution concentrations at the locations of the relevant sensors;

(2) Calculate the differences between the theoretical estimates and actual measurements obtained from the sensors;

(3) Use statistical analysis to compare the differences with reference-value differences obtained during commissioning of the system.

The failure-detection process is undertaken independently of the ventilation control process itself. In this respect, the method differs from that used in the more comprehensive ventilation control process MPVC (e.g. Azuma *et al*, 2011) in which sensor-error can be detected during unsteady-flow conditions, even in long tunnels or in tunnel networks. The latter are much less common than single-tube tunnels, but they exist in many countries (e.g. Maeda *et al*, 2003).

2. SOURCES OF ERROR IN SENSOR MEASUREMENTS

2.1. Traffic Flow

Traffic counters, typically installed at tunnel portals, can measure the type of vehicle (large or small), the time of passing, and the velocity at the time of passing. Using these measurements, it is possible to estimate the location and velocity of all vehicles in a tunnel at any instant (see Eq.1 below). The estimation methods can range from simple extrapolation to complex traffic simulators, but all depend upon the raw data from the traffic sensors themselves. Several types of traffic counters are available – e.g. conventional loop detectors, laser traffic counters and video – and each has advantages and disadvantages. For example, video traffic counters perform less well in poor weather conditions such as heavy rain or snow than they do in good conditions. For all types, appropriate maintenance is necessary.

2.2. Longitudinal Air Flow Rate

The longitudinal air flow rate along a tunnel cannot be measured directly in a manner that is practicable during routine operation. Instead, air velocities are measured and are used to estimate mean velocities and hence flow rates. The accuracy of the inferred flow rates depends upon (i) the accuracy of the actual velocity measurements and (ii) the accuracy of the assumed relationship between these measurements and the flow rate.

Longitudinal AV meters are usually installed at locations where the longitudinal AV is relatively uniform. Often, ultrasonic sensors are used and there are two basic types, in both of which the device has two components mounted some distance apart. With small sized AV meters, both components are mounted on the same wall of the tunnel a few 100's mm apart and a small distance from the wall. With large sized AV meters, the components are typically about 10m apart and on opposite walls of the tunnel, often above the main traffic space.

It is well known that AV measurement errors can become large when a single, small sized AV meter is used in a two-way traffic tunnel - because the longitudinal AV differs significantly on inbound and outbound lanes. Also, even when AV meters are installed in the best possible locations, they are inevitably affected by the air flow disturbances due to vehicle movements. As a consequence, air velocity measurements are usually averaged before being used for control purposes.

In addition to the above difficulties in estimating air flows, the accuracy of measurements from the sensors can deteriorate when material accumulates on their transmitters and receivers so appropriate maintenance is always necessary.

2.3. Pollution Density

In reasonably steady conditions, pollution concentrations in tunnels increase in the direction of air flow. Accordingly, pollution sensors are usually installed a small distance from tunnel portals. In one-way tunnels, only one portal need be instrumented, but in two-way tunnels, sensors are needed at both portals. Ideally, there should be sensors on both walls, but this is not as important as it is for the measurement of air velocity.

VI, CO and NO_2 meters are widely used. Until relatively recently, VI was by far the most important of these (in Japan), but reductions in emissions from large vehicles are causing more attention to be paid to the measurement of CO and NO_2. Quite strong spatial variations in pollution concentrations can exist and these cause readings to vary in time. Therefore, in common with velocity sensors, the measured data are averaged before use in control.

VI meters measure optical transmittance. There are several methods of doing so, but in all cases, the window used in the sensor can be affected by dust and other contaminants, so regular maintenance is needed (especially cleaning). CO and NO_2 meters use electro-chemical sensors, which deteriorate slowly and need calibration or replacement, perhaps once or more each year. All meters that use sampling methods need special care to avoid clogged filters or pump malfunction.

3. LONGITUDINAL VENTILATION MODELS

3.1. Traffic Flow

Traffic flow in the tunnel is the primary cause of longitudinal air velocities and of pollution. In principle, the error-detection process could utilize any reasonable traffic prediction model – e.g. simple extrapolation of measurements from a single TC sensor or even the use of historical traffic data. However, greater accuracy may be expected with models that include algorithms that mimic real behavior. The model used herein is called a

"Car Following Model" because the assumed acceleration of any particular vehicle at any instant is determined from instantaneous values of (i) its speed and (ii) the speed of the vehicle in front. This behavior is represented by the equation:

$$\dot{V}_T(t + t_d, i - 1) = \alpha\{V_T(t,i) - V_T(t,i-1)\} \quad (1)$$

in which V_T and $\dot{V}_T$ denote speed and acceleration, i denotes a particular vehicle, t is time, t_d is a delay time and α is a parameter that controls the rate at which the distance between the vehicles evolves. With this model, the speed of each vehicle is influenced by the speeds of all vehicles in front of it. The model does not take explicit account of the distance between individual vehicles, but its input is real data from the traffic sensors so the initial distances will be realistic and appropriate choices of α can ensure that this remains true throughout the journey through the tunnel.

3.2. Longitudinal Air Velocity

The average air velocity over a cross section of longitudinal tunnel, referred to simply as longitudinal AV, is determined by (i) natural ventilation caused by air pressure difference between the two exit portals, (ii) vehicle drag, (iii) jet fans and other fans and (iv) tunnel resistance. The longitudinal AV in single tube tunnel is uniform along the tunnel (assuming incompressible flow). Using Newton's second law of motion, the longitudinal acceleration of the air at any instant, $\dot{V}_R(t)$, satisfies:

$$\rho A_R L \dot{V}_R(t) = F_N(t) + F_T(t) + F_J(t) - F_R(t) \quad (2)$$

where $F_N(t)$ is the natural ventilation force, $F_T(t)$ is the piston ventilation force, $F_J(t)$ is the fan thrust, $F_R(t)$ is the tunnel resistance force, ρ is the air density and L is the tunnel length. The evaluation of the various forces is undertaken in the usual manner and need not be written in detail here. However, for completeness, it is emphasized that the piston force must be evaluated separately for (a) small and large vehicles and (b) traffic in opposite directions. Thus the overall piston force is

$$F_T(t) = \frac{\rho}{2} A_{TL} \left\{ \sum_{i=1}^{N_{UL}} \left(V_T(t,i) - V_R(t)\right)^2 - \sum_{i=1}^{N_{DL}} \left(V_T(t,i) - V_R(t)\right)^2 \right\} + \frac{\rho}{2} A_{TS} \left\{ \sum_{i=1}^{N_{US}} \left(V_T(t,i) - V_R(t)\right)^2 - \sum_{i=1}^{N_{DS}} \left(V_T(t,i) - V_R(t)\right)^2 \right\} \quad (3)$$

Strictly, Eq.3 is written for the usual case where all vehicles experience a headwind. Within the software itself, the expressions $(V_T\text{-}V_R)^2$ are replaced by $(V_T\text{-}V_R)\,|V_T\text{-}V_R|$ to allow for cases where vehicles experience a tailwind.

3.3. Pollution Concentrations

Vehicle exhaust emissions and road dust are the primary sources of air pollution in tunnels. It is assumed herein that the pollution is transported at air speed and that diffusion may be neglected. This is an acceptable approximation for present purposes. It simplifies the analysis without introducing errors as large as those arising from other approximations (e.g. quasi-steady flow). In this case, the only equation needed to express pollution transport is the continuity equation. For this purpose, the tunnel is regarded as a series of control volumes, each of length Δx, and the rate of change of concentration $\dot{C}_k(t)$ in any particular volume (box) k satisfies:

$$\Delta x \dot{C}_k(t) = V_R \left(C_{k-1}(t) - C_k(t) \right) + \mu_k(t) \tag{4}$$

where $C_{k-1}(t)$ and $C_k(t)$ denote concentrations at inflow and outflow to/from the box and $\mu_k(t)$ describes the local pollution source rate (exhaust emissions, road dust, etc).

Equation 4 is used independently for each pollution type (CO, NO_2, etc) and the pollution source rates are sums of values from all sources. For example, the contributions from vehicle exhausts are expressed as

$$\mu_k(t) = \mu_L\big(N_{UL}(t,k) + N_{DL}(t,k)\big) + \mu_S\big(N_{US}(t,k) + N_{DS}(t,k)\big) \tag{5}$$

in which μ_L and μ_S denote average rates from all large vehicles and all small vehicles in the box respectively. In the software, values are deduced independently for each individual vehicle.

4. DETECTION OF SENSOR FAILURE

4.1. Calibration of the Base Data

Notwithstanding the slow rate of change of base data, it is inevitable that some tunnel-specific dependence will exist overall – e.g. the assumed characteristics of the tunnel, the fan performance and, perhaps also the particular vehicle types within the broad categories of "small" and "large" considered above. Accordingly, when the failure-detection system is first installed (and, ideally, every few years thereafter – perhaps 5 to 10) the self-consistency of the data should be assessed. For this purpose, a two-stage assessment is required. First, the predicted air speeds are compared with measured speeds during different periods of traffic operation – morning, evening, night, weekday, weekend, etc. The base data are then adjusted to give the overall best-fit. Then, predictions of pollution concentrations are compared with measured values and are used to deduce best-fit values of the vehicle-emission parameters.

This process can be undertaken in many different ways, but all reasonable ones should yield similar results. Thereafter, the data can be used with confidence in the failure-detection system.

As an aside, it is interesting to note that even new sensors in good working order are not 100% perfect. Strictly speaking, therefore, if differences detected in the calibration process are minimized exclusively by adjusting input data for the prediction tool, the adjustments will include bias to compensate for sensor inaccuracy. At first sight, this might seem illogical or, at best, a deficiency of the failure-detection methodology. In fact, however, it can be considered to be a significant benefit. This is because the real need is to detect significant *change* in the performance of sensors. Any gross malfunction in their initial behavior should be readily detected during the calibration process. Thereafter, it would be unhelpful to have a permanent bias that has existed from the outset.

4.2. Estimation and Use of "Normal" Differences

The calibration process described in Section 4.1 utilizes measured data over a long period. During this time, the ventilation control system is active, but the failure-detection methodology has not yet been activated. This avoids the risk of an initial period of sub-standard detection leading to false alarms or undetected malfunctions. Either of these outcomes would reduce operator confidence in the process after calibration.

The first purpose of the calibration period is to assess the most suitable values of the base data. To determine these, use is made of measured data over a long period. In principle, the method used to deduce the optimum base data involves assessing many trial sets of base values and then choosing the particular set that gives the minimum statistical variations from the measured values.

An automatic consequence of the above process is the identification of the particular set of statistical data that is applicable for the chosen values of base data to be used in actual operation. That is, the statistical performance of each sensor is known for typical traffic conditions in the tunnel.

When the failure-detection algorithms are implemented in the real tunnel, statistical data describing ongoing differences between measured and predicted values are continually revised and updated. If all is well, the statistical data obtained over sufficiently long periods should be a fairly close match with the corresponding values obtained during calibration. Accordingly, alarms should be raised only when the actual values differ substantially from the calibration values.

It is suggested that the allowable margin should initially be set at a relatively large value and that this should be reduced slowly over a period of months until the smallest value is found that causes no false alarms (or an acceptably small number thereof). This should be done independently for each velocity and pollution sensor.

Let σ_0 denote the standard deviation in the optimum calibration case at a particular sensor and σ_1 denote the evolving standard deviation during actual operation. Then small values of the ratio σ_1/σ_0 will be indicative of a valid sensor and large values will be indication that the sensor is probably faulty. It is provisionally recommended that a value of about 3 is appropriate for defining the boundary between “probably satisfactory” and “probably malfunctioning”. However, this value will not be universally suitable; the most appropriate choice will depend upon factors such as (i) the variability of traffic conditions, (ii) the frequency of changes to external atmospheric conditions and (iii) the frequency with which the control system adjusts fan settings. All of these factors influence the validity of the assumption of quasi-steady conditions that underlies the particular methodology described herein.

4.3. Illustrative Example

Figure 1 shows scatter charts for measured and predicted values of air velocity and visibility index in the Kawasaki Koro Tunnel. The measured values were used to deduce optimum values of the base data used in the theoretical predictions. Thus, the variations shown in the figure are indicative of “normal” scatter. We note in passing that the VI sensor appears to have an offset (a best-fit straight line would not pass through the origin). This was not detected before undertaking the present work.

Figure 2 shows evolving differences between measured and predicted values of AV and VI. The figure includes a time when sensor malfunction occurred. This particular incident is pronounced and so it is easily detected visually. However, visual detection is possible only when the data are inspected by a human being – perhaps weeks or months after the event itself. A valuable benefit of the automatic detection process is that failure can be detected quickly, typically within hours or even within minutes in the case of serious failure. This particular malfunction occurred during cleaning of the tunnel by washing its walls. As a consequence, the malfunction occurred simultaneously in the AV and VI sensors. More commonly, failure of one sensor will not be accompanied by the failure of other sensors.

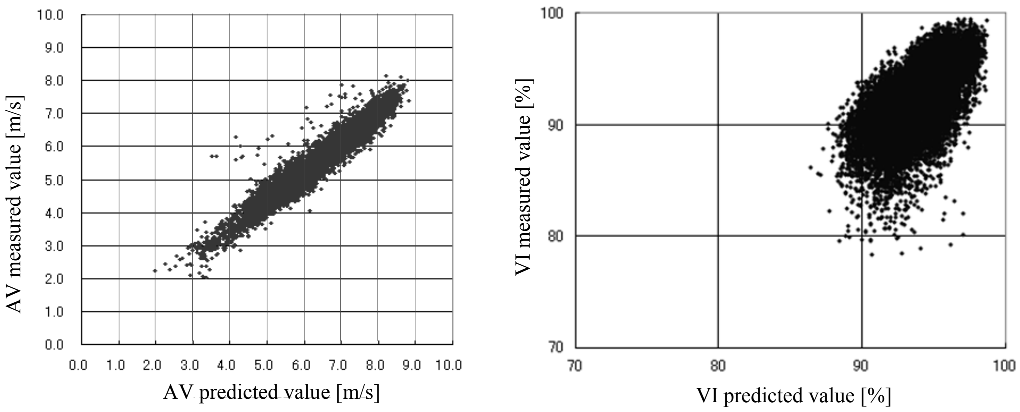

Figure 1: Comparison of predicted and measured values of AV and VI

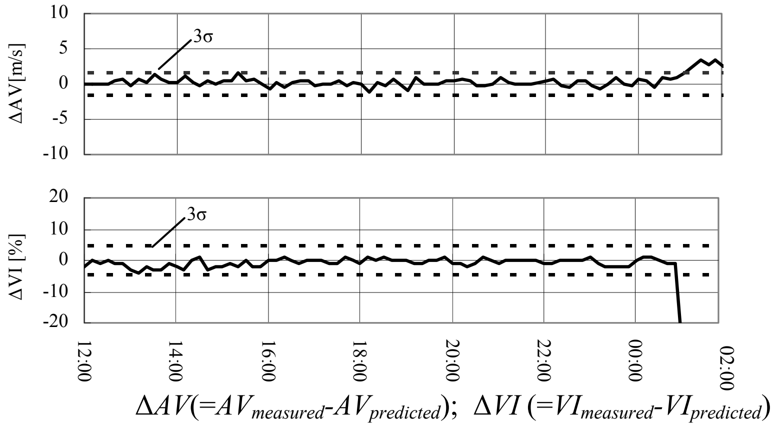

Figure 2: Sensor failure at approximately 01:00 hours

4.4. Cascade failures

So far, it has been assumed that unusually large differences detected at any particular sensor will be indicative of problems with that sensor. However, this is not necessarily so. Consider, for instance, the consequences of malfunction in the traffic sensors. This will result in false data being processed in the air speed module of the prediction tool so the predicted air speed will necessarily differ from the measured value. As a consequence, the pollution module will be supplied with false data for air speeds as well as for traffic flows. Therefore all sensors will appear to fail simultaneously. Since this outcome is most unlikely to occur as a consequence of faults in each individual sensor, the post-processing software should not treat it as such. Instead, it should trigger a warning that a wider problem exists and that the malfunction of a TC sensor is one possible cause.

Another example of false alarms with pollution sensors can arise when the true malfunction is at an air speed sensor. This will be possible if the value of the air speed passed to the pollution module is a weighted average of the predicted and measured air speeds. Such averaging can have significant benefits when the AV sensors are performing well so its use should not be discounted without careful thought. How can we allow for the possibility of cascade failures such as this? One possibility is to have two independent predictions for pollution concentrations, namely one based exclusively on the predicted air speed and one based on a weighted average of the predicted and measured values. If both models indicate pollution sensor error, the prediction is probably correct. If only the second of the models indicates pollution sensor error, it will be more likely that the problem lies with the AV sensor.

5. CONCLUSIONS

This paper has presented a failure detection method for TC, AV, VI, and CO meters in routine tunnel operation. The method makes statistical comparisons between measured values and values predicted by air speed and pollution models based on quasi-steady approximations to air flows. The following statements summarise the key messages of the paper:

(1) Measurements of traffic data at tunnel portals can be used to predict evolving air velocities and pollutions concentrations throughout a tunnel;

(2) By analyzing measured data over sufficiently long periods, it is possible to infer realistic approximations for values of base data describing tunnel and vehicle characteristics;

(3) As a by-product of the method of determining optimal values for the base data, quantifiable statistical data are obtained about expected deviations between measured and predicted values at any particular sensor;

(4) By monitoring statistical variations at sensors during actual tunnel operation and comparing them with the expected variations, it is possible to detect significant variations from normal behavior and hence to identify instances of probable sensor malfunctions.

6. REFERENCES

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