WEB-SCADA: A WEB-BASED SUPERVISORY CONTROL AND DATA ACQUISITION PLATFORM FOR ROAD TUNNEL SAFETY IN JAPAN

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ABSTRACT

The proposed paper introduces a web-based, remote-access platform for tunnel supervisory control and data acquisition ("SCADA"). The system enables operators and emergency services to monitor safety systems (e.g. fire detection and location) and ventilation systems, and to activate desired responses. The platform consists of an operational technology (OT) layer where real-time data is collected in a conventional database, and an information technology (IT) layer where web-based technology has replaced conventional display methods on monitoring screens.

We propose a Web-SCADA architecture built on the latest web technology. It is designed to support ubiquitous monitoring, with data displayed not only on conventional PC screens at the control centre, but also on tablets and smartphone screens in the office or even at home. By enabling direct access to the data in this way, the system facilitates fast responses by the police and fire services as well as by tunnel controllers. Also, by ensuring that everyone has access to the same up-to-date information, it enhances both the speed and reliability of information transfer, frees up humans for other tasks, and reduces the risk of potentially-flawed human communication. Simulation-based modelling is integrated into the web-SCADA to extend the real-time modelling with forecasts of the potential development of conditions (e.g. fire and smoke propagation). The modelling also assists in the detection of potential failures of sensors and other equipment.

Overall, the platform represents a significant enhancement of tunnel management whilst simultaneously reducing the need for human resources (a particular concern in Japan). It is expected to enhance both safety and operational efficiency.

Keywords: Web-based SCADA; Multimodal perception; Real-time simulation; Fire detection

1. INTRODUCTION

Road tunnel safety demands rapid incident detection, coordinated response, and precise ventilation control. This paper proposes Web-SCADA, a web-based supervision architecture that integrates multimodal sensing, edge inference and model-based simulation to support rapid incident detection and operational decision-making. The system introduces a modular OT/IT architecture enabling end-to-end data flow from sensors to simulation and visualization, probabilistic model-based decision support for operators, and an operational sensor-health monitoring module based on the variance-ratio (σ_1/σ_0) method for detecting and isolating faulty telemetry. The paper presents three original contributions: (i) a modular web-based SCADA architecture for tunnel supervision, (ii) an integrated multimodal perception and data-fusion approach within SCADA, and (iii) the integration of simulation modules for predictive monitoring and sensor-health assessment.

Scope and limitations. The architecture presented here is a vendor-neutral design and a research prototype. While selected modules have been prototyped by the authors, this paper primarily outlines the proposed architecture, design rationale and example workflows; full experimental validation and large-scale deployment remain topics for future work.

2. TECHNOLOGICAL CHOICES

We select a modern, modular web architecture: PHP (Laravel) on the server side for the API, job orchestration and workflow management; Vue.js on the client side for a reactive, responsive UI that can be adapted to different roles (operators, firefighters, other stakeholders); MySQL as the primary transactional database for configuration, sensor data, events (alerts), tickets and simulation outputs; and Python for the model-base (simulations and scientific computations), which writes its results into the SQL database consumed by the web-SCADA. Multi-channel notifications (email, SMS, LINE for Japan, Slack for enterprise) are handled asynchronously via Laravel queues to ensure retries and traceability.

This choice builds on the “web-SCADA” paradigm documented in the literature [1] - early Web/Java implementations around 1995–2000 demonstrated the feasibility of browser-based supervisory control and lightweight client deployment, advantages that we exploit here using contemporary, industrially supported technologies.

For field data acquisition, the architecture uses a programmable logic controller (PLC) to perform direct sensor reading (AV, CO, VI, traffic counters, I/O) and to manage local real-time control logic. Complementarily, an edge inference module (YOLOv5) may be deployed on an edge device connected to cameras to reduce latency and bandwidth; both PLC and edge streams are then integrated into the web-SCADA supervision layer.

3. EQUIPMENT AND MULTIMODAL PERCEPTION

The detection and supervision system relies on multimodal perception combining the following sensors:

- Dual thermal + optical cameras - rapid thermal detection and visual classification, with the optical channel used for image-based inference (e.g., YOLOv5). [2]
- Acoustic microphones / arrays - audio signatures for collisions, tyre bursts, horns or voices; valuable in low-visibility conditions. [3]
- Linear temperature sensing cable - continuous temperature measurement along the ceiling with metre-scale localisation for fast pre-alarm confirmation. [4]
- Variable-speed (inverter) jet-fans - ventilation actuators supporting demand-driven / zero-flow strategies and accepting model-based setpoints. [5]
- Traffic counters (visible / thermal modes) - vehicle counts and class estimates feeding the model-base.
- VI / CO / AV probes - visibility index (VI), carbon monoxide (CO) and longitudinal air velocity (AV) sensors supplying quantitative inputs to the simulator.

Sensor streams (video, audio, probe measurements, linear-temperature traces and counts) are time-synchronized to enable multimodal fusion and corroborated alerts.

4. SYSTEM ARCHITECTURE AND CYBERSECURITY

The proposed system architecture follows a layered and modular design, connecting on-site sensors and control devices in the tunnel to a local monitoring and supervision platform hosted in the control room. All field data are acquired through industrial interfaces and transferred securely to the local SCADA server for visualization, analysis, and decision support (see Annex 1 for the architecture diagram).

4.1. Field layer - tunnel instrumentation

For the purpose of illustration, the scenarios in this paper assume a hypothetical tunnel instrumented with the sensors listed in Section 3, deployed and cabled to provide synchronized telemetry to the local PLC and SCADA server. Field signals include sampled probe measurements (VI, CO, AV), event streams (count, detection bounding boxes), continuous linear-temperature traces and archived video/audio.

4.2. Control and monitoring rooms

In a typical deployment, the electrical room would include an inverter panel which controls the variable-speed jet-fans (JF), and the control panel which collects signals from field sensors (AV, CO, VI, TC, linear temperature cable). A LAN cable connects the electrical room to the monitoring room, where the local web server and SQL database are installed. Sensor readings and events (video, acoustic, linear-temperature and probe measurements) are stored as structured SQL data, while video recordings are archived as MP4 files. The monitoring system can operate offline (without internet connection) for safety and independence. When connected to the internet, remote access to the web server is possible through a secure VPN, allowing authorized operators, maintenance teams and external stakeholders (e.g., emergency services) to monitor the system and receive notifications.

4.3. Cybersecurity considerations

Following industrial best practices [6], the system applies a multi-layer security posture: end-to-end encryption, multi-factor authentication for remote/VPN access, continuous IDS logging, and strict network segmentation/firewalls isolating PLC/control networks. Operational policies for patching, access control and audit logging complete the protection strategy.

5. HMI / HCI: OPERATOR INTERFACE AND USABILITY

As highlighted in the same reference [6], operator experience is critical to the effectiveness of SCADA systems. This section summarizes the design goals and usability considerations of the monitoring interface, focusing on role-adapted presentation, rapid situational awareness, and support for decision-making under stress.

5.1. Main monitoring view and role-based notifications

The monitoring screen is organised as a single operational view that presents critical information with minimal navigation (see Annex 2 for a screenshot). The central video panel shows the selected camera pair (thermal + visible) with adjacent pairs as thumbnails; a linear temperature ribbon overlays thermal readings and active detections and indicates the precise location of a detected fire, while intervention devices (e.g. water spray) and their status are shown in context. Beneath the video, a compact sensor panel reports key environmental and ventilation values (VI, CO, AV) and jet-fan rotation rate, and a status table summarises active alerts and severity. Each operator has a personal notifications page listing alerts, comments and required actions; notifications may also be pushed to external channels (email, SMS, LINE, Slack) and filtered by type (e.g. fire only). A simplified, mobile-oriented view for emergency responders prioritises essential items only (fire location, presence of people, AV/direction, estimated time of arrival to ventilation target, thermal camera access and escape-route status).

5.2. User testing and planned evaluations

Preliminary user testing was performed iteratively to validate interaction concepts and prioritize design decisions. Early tests involved eight external participants across multiple regions and devices; their feedback guided incremental improvements to the layout, alert prioritization and responsiveness. Future evaluations will target the actual user populations (tunnel operators and emergency responders) and will include formal usability assessments with quantitative metrics such as detection and decision times, error rates, and subjective usability scores.

6. USE OF THE MODEL-BASE IN FIRE SCENARIOS

At the start of the processing chain, YOLOv5 is employed as the vehicle-classification module: its primary role is to detect and classify objects (cars, buses, trucks, etc.) in real time and to estimate their approximate dimensions from camera imagery. The vehicle class information is then mapped to an initial estimate of the fire scale (heat release rate, HRR, in MW) using type-conditioned prior distributions (national tables / PIARC) and an image→HRR calibration. In this way, visual classification does not merely describe traffic; it provides the key input—or a probabilistic prior—required to initialize the fire simulation and to predict subsequent smoke and ventilation dynamics.

6.1. Proposed architecture - detection and classification

YOLOv5 is deployed at the edge of existing camera streams (visible or thermal) to deliver low-latency vehicle type and size estimates. Importantly, YOLOv5 can be applied to any camera type, but satisfactory performance on a given sensor requires fine-tuning on images acquired from that sensor. The detector outputs both a class label and an uncertainty score; this uncertainty is propagated into the probabilistic HRR estimate used by the simulator. The presence of smoke, occlusions or adverse viewing angles degrades classification reliability and must therefore be reflected in the weighting of priors and in the confidence communicated to operators.

6.2. Fire-scale (HRR) selection - indicative table

To define design-fire scenarios, we rely on published ranges from PIARC [7], national guidance [9], and experimental findings from Nakahori et al. [13]. The indicative HRR ranges and the nominal values adopted in this work for simulation experiments are summarized in Annex 3.

6.3. Role and utility of the model-base in a fire

The model-base is a computationally light, fast simulation that ingests: (i) an initial fire-scale estimate (from YOLOv5 and/or operator input), (ii) traffic counts and flows from the traffic counter, and (iii) the pre-event state of tunnel sensors (visibility, CO, longitudinal air velocity AV, etc.). From these inputs the simulator produces near-real-time outputs: (a) smoke propagation forecasts (arrival times and estimated VI per tunnel section), (b) traffic and congestion evolution (vehicle positions and evacuation probabilities), (c) the temporal trajectory of longitudinal air velocity (AV) and the estimated time-to-target (e.g. $AV \rightarrow 0$ $m \cdot s^{-1}$), and (d) operational recommendations for jet-fan (JF) rotational speeds to balance evacuation facilitation and smoke control. The operational aim is to supply operators and emergency responders with actionable quantities (median and uncertainty intervals) that support safe, timely and documented evacuation decisions.

6.4. Software implementation and real-time pipeline

The simulation framework is implemented in Python. Structured prediction outputs are periodically written to a relational SQL database. A web-based SCADA frontend reads these records in real time (API / WebSocket) and visualizes: smoke arrival maps, AV time series, recommended JF setpoints and associated confidence metrics. The operational loop is therefore: sensor detection (camera / audio) → initial HRR estimate (AI ± operator) → fast simulation → write predictions to SQL → SCADA read/display → human decision/action. The model-base is subject to regular recalibration - parameter priors and image→HRR mappings are updated from operational feedback, simulation studies and available experimental data - to limit model drift and preserve prediction fidelity.

6.5. Methodological detail

The mathematical formulation of the model-base - covering vehicle dynamics, longitudinal airflow, jet-fan control and smoke advection - is summarised here; full equations and implementation notes are provided in Annex 6 (see also Annex 5 for nomenclature).

The traffic module computes vehicle positions, types and speeds at one-second intervals; traffic volume Mt ($veh \cdot h^{-1}$) and mean speed Vt ($km \cdot h^{-1}$) set the mean vehicle spacing $\Delta x = (Vt \cdot 1000)/Mt$. Vehicle motion uses an Optimal Velocity Model (OVM) to derive target speeds and accelerations as functions of headway, with simple stop-logic for vehicles affected by incidents.

Airflow dynamics are modelled by per-section momentum balances: portal pressure differences (natural ventilation), the piston effect of traffic, thrust from jet-fans, and frictional/resistive losses are combined to yield longitudinal velocity states used by the simulator. When a fire is detected, according to zero-flow strategy, jet-fan operation is represented by a feedback controller (PID-like) that computes target rotation/thrust setpoints from deviations between measured and desired air velocity; actuator limits and anti-windup are applied in practice.

Smoke is represented by an extinction coefficient (x,t) (m^{-1}) whose transport is computed with a 1-D advection–diffusion equation augmented by fire source terms parameterised from HRR(t). The simulator couples these modules in real time to produce forecasts (smoke arrival, visibility, AV trajectory) and recommended JF setpoints; probabilistic updates and Bayesian refinement of priors from operational feedback are also supported. See Annex 6 for the full model equations, discretisation, parameter values and numerical notes.

6.6. Operational benefit for evacuation

By combining an initial, classifier-driven fire-scale estimate with a fast, uncertainty-aware simulator, the system yields critical spatio-temporal horizons (e.g., time available before smoke reaches a given section; time until AV meets a specified threshold). Presenting these forecasts with quantified uncertainty in the web-SCADA console materially improves the ability of operators and fire crews to coordinate evacuations, select safe ingress/egress routes, and sequence ventilation actions. Crucially, the human operator remains in the loop: when classifier confidence is low or uncertainty bands are wide, operator validation or override can be requested before automated recommendations are enacted.

7. SENSOR-FAILURE DETECTION FOR ROUTINE OPERATION

We adopt the variance-ratio σ_1/σ_0 method [10] (Annex 5 - Nomenclature) as a lightweight, operational data-quality monitor validated in case studies. The method compares the short-term residual standard deviation σ_1 (measured − predicted over a short operational window) with a reference σ_0 established during a long calibration period; σ-ratio(t) = σ_1/σ_0. Values near 1 indicate healthy sensors, while sustained values $\gg 1$ indicate suspect telemetry. Typical thresholds and an illustrative calculation and rolling-plot are provided in Annex 4. The module provides three practical outputs for operators: (i) early anomaly detection; (ii) temporal evidence (residual time series and plots) to support visual verification; and (iii) ranked, timestamped alerts to prioritise maintenance and enable audit.

7.1. Recommended operator procedures (practical examples)

We propose the following operational procedure, implemented in the web-based SCADA as alerts and action buttons. Computation and thresholds (indicative, to be calibrated): compute σ_1 continuously over a short window (W_short ≈ 5–30 min), with σ_0 derived from a long calibration period. Raise an alert if `σ₁/σ₀ ≥ 3` and the condition persists for `T_confirm ≈ 5–15 min`.

- Level 1 - Warning (elevated σ-ratio, short persistence): display a yellow indicator in the sensor-health panel and notify the operator. Recommended action: monitor the sensor, visually inspect correlated camera frames, collect logs and schedule an inspection if the anomaly recurs.
- Level 2 - Critical (elevated σ-ratio with persistence > T_confirm): display a red indicator, tag the telemetry as “suspect”, and recommend actions: (i) switch affected automatic control loops to manual, (ii) create a high-priority maintenance ticket, (iii) temporarily exclude suspect data from automatic control loops if severity warrants.

Validation actions: the operator must compare the alert against available evidence (camera frames, short audio snippets, residual evolution) and choose an action (`acknowledge` / `defer`/ `escalate`). All operator decisions are timestamped and stored for audit.

7.2. UI / SCADA integration

In the web interface each sensor shall expose a compact “health indicator” showing status (OK / WARN / FAULT), the current σ-ratio value, a small residual plot (last 24 h) and action buttons (Acknowledge / Isolate / Create ticket). For critical alerts the system can auto-populate an incident report with residual plots, representative image(s) and the suspicious time window to assist field crews.

7.3. Practical limitations and uncaptured phenomena

The σ-ratio method is robust and operationally simple but has well-known limitations that should be communicated to operators:

- Slow drifts. Progressive offsets (slow bias) may not be detected by variance monitoring alone; σ-ratio is relatively insensitive to slow mean shifts.

- Cascade failures. A faulty traffic counter (TC) or other reference sensor may generate correlated residuals across many derived predictions, producing multiple alerts; σ-ratio alone will not identify the root cause. In such cases operators must cross-check other sources (cameras, logs, external data) before executing maintenance.
- Benign external events. Legitimate transient events (heavy rain, tunnel cleaning operations, large traffic surges) can temporarily increase σ_1/σ_0; persistence logic and visual validation are therefore essential to limit false positives.

7.4. Outlook - future methods

For reference and future development (but not as part of the initial operational deployment), the σ-ratio module can be complemented by more sensitive and diagnostic techniques: EWMA/CUSUM procedures for detecting slow drifts [11], regularized Mahalanobis-type multivariate monitoring for identifying cascade failures [12], or multivariate machine learning (ML) methods to classify fault types. These extensions require separate development and systematic validation (simulation and fault injection) and are therefore planned as subsequent enhancements to the baseline σ-ratio solution, rather than as a substitute for the validated, operationally ready method adopted here.

8. SUMMARY AND CONCLUSION

In practice, the proposed system enhances situational awareness and shortens the response time of first responders by combining multimodal evidence and predictive simulation within a single web-based interface. Overall, the web-SCADA framework provides a practical and scalable approach to tunnel incident detection, forecasting, and operational coordination by delivering synchronized, uncertainty-aware predictions and ventilation recommendations to operators and emergency services. Future work will include simulation and experimental validation campaigns to quantify performance gains, usability studies with operators and emergency responders, enhanced system resilience for large-scale deployment and continued efforts toward AI-based diagnostic methods.

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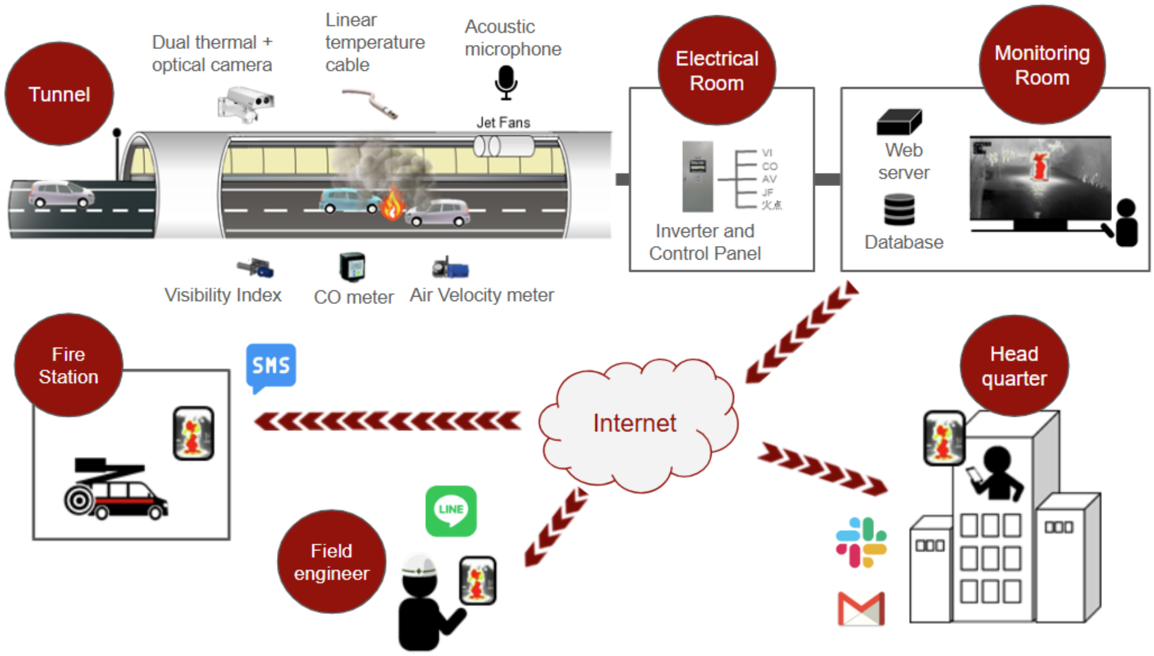
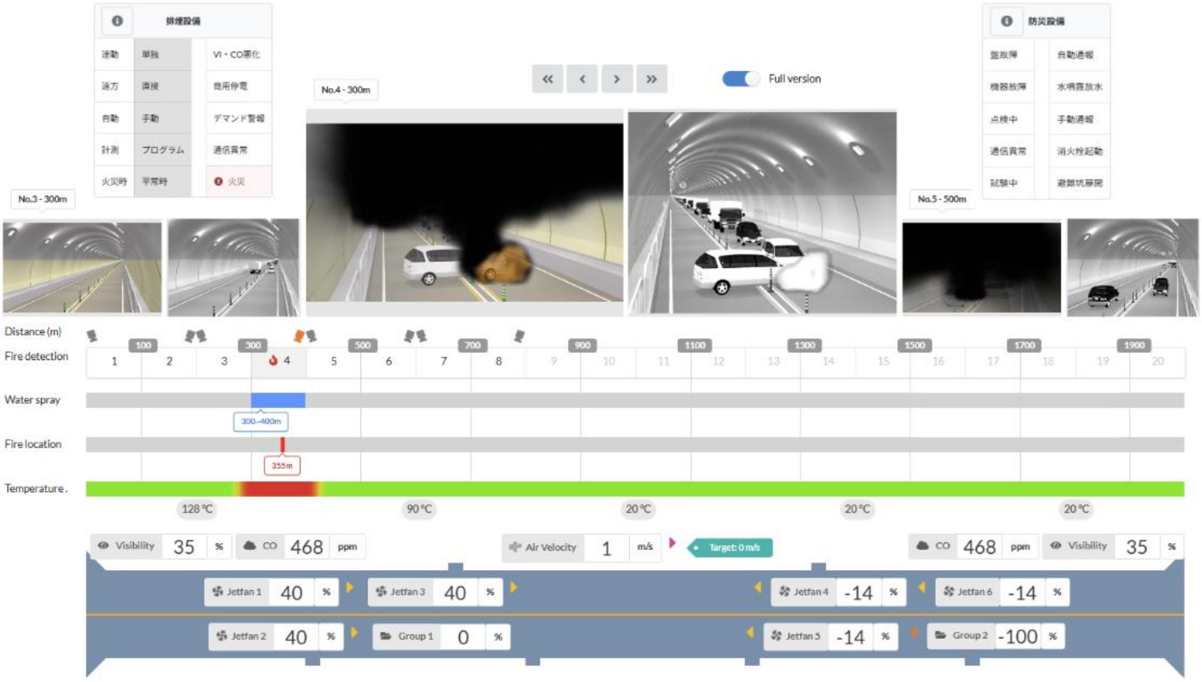
10. ANNEXES



Annex 1: Architecture diagram

Note: This diagram illustrates the layered and modular SCADA system connecting field devices to the control room platform, highlighting data flow and interfaces.



Visibility 35 %
CO 468 ppm
Air Velocity 1 m/s
Target: 0 m/s
CO 468 ppm
Visibility 35 %
Jetfan 1 40 %
Jetfan 3 40 %
Jetfan 4 -14 %
Jetfan 6 -14 %
Jetfan 2 40 %
Group 1 0 %
Jetfan 5 -14 %
Group 2 -100 %

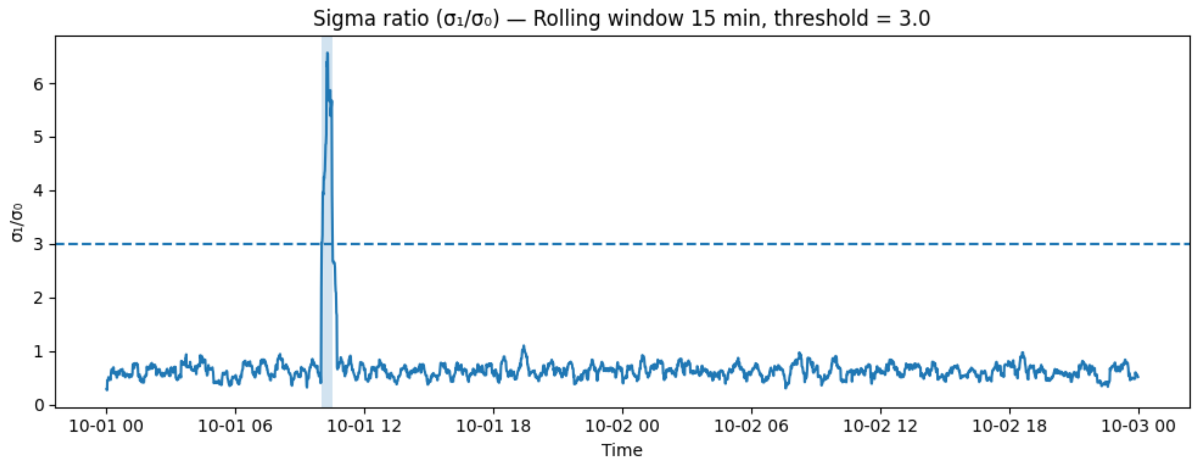
Annex 2: Screenshot of the monitoring screen

Note: This figure illustrates the main operational view of the SCADA system, including video feeds, sensor panels, ventilation status, and alert tables, providing a consolidated interface for tunnel operators.

Vehicle type / scenario	Indicative HRR range (MW)	Nominal value used (MW)
Passenger car	2 - 8	5
Bus / coach	10 - 30	20
Small loaded truck	20 - 50	30
Large loaded truck / HGV	50 - 150	100
Pool fire / tanker leak	100 - 300	200

Annex 3: Indicative HRR ranges

Note: These values are indicative design-fires. Battery fires and special cargoes can significantly deviate from these medians; consequently, the HRR estimate is treated probabilistically (type-conditioned prior + online update). The European Directive 2004/54/EC [8] frames tunnel-safety requirements but does not mandate fixed HRR values; selection of design-fires remains a national/engineering decision.



Annex 4: Sigma ratio (σ_1/σ_0) - rolling-window σ_1 divided by σ_0 with a dashed line for the threshold (3.0).

Note: Rolling-window σ_1 divided by σ_0, with a dashed line indicating the threshold (≈ 3.0). This visualization illustrates how persistent deviations trigger critical alerts for suspect sensors. Example: $\sigma_0 = 0.5$, $\sigma_1 = 1.6 \rightarrow \sigma\text{-ratio} = 3.2$

Annex 5: Nomenclature

Symbols

σ_0 - Reference standard deviation (calibration period)
σ_1 - Short-term residual standard deviation (operational window)
σ-ratio(t) - σ_1/σ_0, variance ratio at time t (dimensionless)
HRR(t) - Heat release rate as a function of time (MW)
Mt - Traffic volume (vehicles per hour, $\mathrm{veh \cdot h^{-1}}$).
Vt - Average traffic speed used to compute spacing ($\mathrm{km \cdot h^{-1}}$).
Δx - Mean vehicle spacing (m).
(Δxi) - Optimal velocity for vehicle i as a function of headway ($\mathrm{m \cdot s^{-1}}$).
Vmax - Maximum vehicle velocity ($\mathrm{m \cdot s^{-1}}$).
hc - Critical headway (m).
Δh - Smoothness parameter for the OVM (m).
a - Sensitivity (reaction) coefficient in OVM ($\mathrm{s^{-1}}$).
i - Vehicle index (integer).
k - Tunnel section index (integer).
ΔPk - Total air pressure difference in section k (Pa).
$\Delta Pn,$ - Pressure difference from natural ventilation in section k (Pa).
$\Delta Pt,$ - Pressure change from piston effect (traffic) in section k (Pa).
$\Delta Pj,$ - Thrust contribution from jet-fans in section k (Pa).
$\Delta Pr,$ - Pressure loss due to resistance in section k (Pa).
Mk - Mass of air in section k (kg).
Vk - Longitudinal air velocity in section k ($\mathrm{m \cdot s^{-1}}$).
Ar, - Cross-sectional area of section k ($\mathrm{m^2}$).
RJtg - Targeted rotation/thrust setpoint for jet-fans (unit depends on controller: rpm or normalized thrust).

Kp, Ki, Kd - Proportional, integral and derivative gains in PID-like controller (units consistent with controller design).
Δt - Controller sampling interval (s).
(x, t) - Smoke extinction coefficient at position x and time t (1·m^{-1}).
$q$out - Volumetric exhaust flow rate (m^{3}·s^{-1}).
D - Effective diffusion/advection coefficient (m^{2}·s^{-1}).
$\xi(x, t)$ - Smoke source term from the fire (1·m^{-1}·s^{-1}, parameterised from HRR).
x - Longitudinal coordinate along tunnel (m).
t - Time (s).
W_short - Short rolling window duration (e.g., 5–30 min)
T_confirm - Confirmation persistence threshold (e.g., 5–15 min)

Acronyms

API - Application Programming Interface
AV - Air velocity (see symbol $Uk/\ Ur$)
CUSUM - Cumulative Sum (statistical method for monitoring shifts in process mean or variance)
ETA - Estimated Time of Arrival (time to reach a given target value, e.g., Air velocity target)
EWMA - Exponentially Weighted Moving Average (statistical process control method for detecting slow changes)
HCI - Human–Computer Interaction
HMI - Human–Machine Interface
HRR - Heat Release Rate (see symbol HRR(t))
IIoT - Industrial Internet of Things
JF - Jet-fan (ventilation actuator)
ML - Machine Learning (data-driven methods for pattern recognition, classification, or prediction)
OVM - Optimal Velocity Model
PLC - Programmable Logic Controller
SCADA - Supervisory Control and Data Acquisition
SQL - Structured Query Language
TC - Traffic Counter
VI - Visibility Index (distance in m)
YOLOv5 - You Only Look Once v5 (object detector)

Annex 6: Model Equations

(See Annex 5 for full nomenclature and units.)

A. Traffic dynamics (OVM and spacing)

$$\Delta x = \frac{V_t \cdot 1000}{M_t} \tag{A1}$$

$$V(\Delta x_i) = V_{max}\left(\tanh\left(\frac{\Delta x_i - h_c}{\Delta h}\right) + \tanh\left(\frac{h_c}{\Delta h}\right)\right) \tag{A2}$$

$$\ddot{x}_i = a(V(\Delta x_i) - \dot{x}_i) \tag{A3}$$

We employ an Optimal Velocity Model (OVM) for vehicle motion; this approach is standard in microscopic traffic modelling and numerical studies [14] (or see eqs. A1–A3).

where:

i - vehicle index; Mt - traffic volume (veh/h); Vt - average speed (km/h); Δx - mean spacing (m); Vmax - maximum vehicle speed (m/s or km/h consistent with Vt); hc - critical headway (m); Δh - smoothness parameter (m); a - sensitivity coefficient (s^{-1}).

B. Longitudinal airflow - pressure balance and section dynamics

Global pressure-balance over tunnel sections:

$$\sum_{k=1}^{i} \Delta P_k = \sum_{k=1}^{i} \left(\Delta P_{n,k} + \Delta P_{t,k} + \Delta P_{j,k} + \Delta P_{r,k}\right) = 0 \tag{A4}$$

Per-section momentum relation (Newtonian form):

$$M_k \frac{dV_k}{dt} = A_{r,k} \Delta P_k = A_{r,k}(\Delta P_{n,k} + \Delta P_{t,k} + \Delta P_{j,k} + \Delta P_{r,k}) \tag{A5}$$

where:

k - section index; ΔPk - total pressure difference (Pa) in section k; $\Delta Pn,k$ - natural ventilation pressure term (Pa); $\Delta Pt,k$ - piston-effect pressure from traffic (Pa); $\Delta Pj,k$ - thrust from jet-fans (Pa); $\Delta Pr,k$ - pressure loss due to resistance (Pa); Mk - mass of air in section k (kg); Vk - average AV in section k (m/s); Ak - cross-sectional area (m^2).

Notes on modelling choices:

- ΔPt, is computed from the summed momentum exchange of vehicles in the section, following OVM-derived traffic states [14].
- ΔPr, is typically modelled using Darcy–Weisbach or empirical friction relations [7,9].
- ΔPj, maps fan rotation to thrust via simplified quadratic laws or manufacturer curves [5].

C. Jet-fan control (PID-like setpoint computation)

Discrete-time controller (sampled at Δt):

$$RJ_{tg}(t) = K_p(V_r(\mathrm{t}) - V_d) + K_i \times \sum_{\tau=t_0}^{t} (V(\tau) - V_d)\, \Delta\mathrm{t} + K_d \frac{V(t) - V(t - \Delta\mathrm{t})}{\Delta t}$$

where:

RJtg - targeted rotation/thrust setpoint for fan(s); V - measured/reported longitudinal AV (m/s); Vd - desired AV (setpoint, m/s, e.g. 0 for zero-flow); Kp, Ki, Kd - controller gains; Δt - controller sampling interval.

Implementation note: in practice we may omit the derivative term (Kd = 0) for robustness and use anti-windup on the integral term when fans saturate. PID-like control for ventilation is widely used in tunnel airflow studies [5].

D. Advection–diffusion of smoke (1-D model)

PDE for smoke extinction coefficient (x, t) (m⁻¹):

$$\frac{\partial C}{\partial t} + \frac{\partial (C V_r)}{\partial x} + \frac{q_{out}}{A_r} C = D \frac{\partial^2 C}{\partial x^2} + \xi_f(x, t) \tag{A7}$$

where:

C - smoke extinction coefficient (m⁻¹); x - longitudinal coordinate (m); Vr - local longitudinal air velocity (m/s); $q$out - exhaust volumetric flow (m³/s); Ar - cross-sectional area (m²); D - effective diffusion/advection coefficient (m²/s); ξf - smoke source term (m⁻¹·s) parameterised from HRR and combustion properties [13].

Discretization & boundary conditions: the PDE is discretized using an upwind or flux-conservative finite-volume scheme consistent with the sectioning used for airflow; boundary conditions at portals reflect ambient exchange and exhaust extraction. The extinction coefficient C is mapped to visibility index (VI) using an empirical relation (e.g., Koschmieder law or tunnel-specific calibration) [7,9] - see Annex 5 for the chosen mapping.