ENHANCEMENTS OF TUNNEL VENTILATION SYSTEM FOR ROAD TUNNELS ADOPTING AERODYNAMIC CONTROL & MONITORING STRATEGIES

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ABSTRACT

Control of tunnel air quality during normal operation and control of smoke under fire emergency are two essential functions of tunnel ventilation system for road tunnels. Effectiveness of these two functions depends on many tunnel design elements such as tunnel alignment, cross-sectional geometry, traffic operations, location of ventilation shafts/plants, control strategy for ventilation and smoke in tunnel, etc. Semi-transverse ventilation strategy is a widely adopted scheme in many vehicular road tunnels worldwide due to its many advantages, in particular its comparative balanced effectiveness between performance of normal ventilation and that of emergency smoke control, over other schemes. There are several major aspects that can be further enhanced to provide a more cost-effective and safer tunnel environment for tunnel users. The paper aims to firstly identify the critical elements affecting the performance of tunnel ventilation system and to illustrate their potential implications to ventilation and smoke control. Secondly, study of feasible technical resolutions to cope with these effects are then introduced and supplemented with some practical examples of ventilation schemes for illustration. Moreover, further review using computer simulation analyses is also conducted for verification of the system performance from aerodynamic and thermodynamic points of view. Furthermore, the system design and implementation with real-time automatic system control and monitoring on relevant tunnel environmental elements are then illustrated including air quality monitoring system, airflow velocity, fire detection system, fire alarm system and associated mechanical/ electrical system design elements. Potential application of Internet-of-Things (IoT) and digital twin technologies for further enhancement of the system operation is also discussed. Last but not the least, the paper shares some case-studies including computer simulation analysis and testing results for tunnel projects to illustrate the practical implementation of these enhancements.

Keywords: Tunnel Ventilation, Smoke Control, Semi-transverse, Fire Safety, Automation, Simulation Analyses

1. INTRODUCTION

In many recent road tunnel projects worldwide, semi-transverse ventilation strategy is a widely adopted scheme due to its many advantages, in particular its comparative balanced performances between ventilation for tunnel air quality control under normal operation and smoke control under emergency operation during congestion and bi-directional traffic conditions respectively [4]. On the other hand, there are several critical elements and design concerns that may affect operational effectiveness and efficiency of this tunnel ventilation scheme. These include tunnel alignment and geometry, traffic operations, control strategy for both ventilation and smoke management in tunnel, etc. The paper aims to firstly identify these critical elements and to illustrate their potential implications to ventilation and smoke control. Study of feasible technical resolutions to cope with these adverse effects are then elaborated in detail with examples of computer simulation analyses and project reference of airflow testing data. Furthermore, the system design and implementation with real-time automatic system control and monitoring on relevant tunnel environmental elements are then discussed. Some innovative ideas of using more comprehensive tunnel and traffic data with Internet-of-Thing (IoT) are further illustrated as potential advancements for system control for future reference.

2. CRITICAL ELEMENTS AFFECTING PERFORMANCE

2.1. Tunnel geometry

Number of lanes and traffic gauge determine major dimensions of the tunnel. Besides, spatial provisions for other facilities (such as maintenance/safety walkway, zones on side wall for Electrical and Mechanical (E&M) equipment installation, ceiling crown and ventilation ducts, etc.) further refine the tunnel geometry. Arrangement of ventilation points along the tunnel shall be designed to suit the tunnel geometry in order to achieve a proper distribution of airflow pattern and pollutant control during normal operation. Moreover, a well-planned arrangement of ventilation points can facilitate efficient smoke extraction and maintain a tenable environment for evacuation during fire emergencies [5].

2.2. Gradient Effect

Pollutant emission rate from vehicles depends on the gradients of road alignment. For example, when the vehicle is running uphill, more fuel is being consumed, and thus more air pollutants are emitted. Under normal operation, the pollutant concentration level is building up along the traffic direction. This becomes a challenge of a semi-transverse tunnel ventilation system to limit the pollutant concentration level for a longer tunnel. Under a fire emergency, the gradient effect acting on smoke spread leads to a challenge in two folds: (1) to confine smoke within certain length for minimizing smoke spread to other sections, and (2) to create a tenable environment for evacuation and firefighting. The buoyancy effect of hot smoke creates a tendency to flow towards uphill direction with a faster smoke accumulation at higher side [6]. If the smoke could not be removed effectively, the escape path could be endangered by dropping of the smoke layer.

2.3. Traffic Flow

The movement of the vehicles inside the tunnel induces certain degree of tunnel airflow (i.e. “piston effect”). The higher the vehicle travelling speed, the larger “piston effect” can be generated. In general, ventilation of tunnel could be achieved with the “piston effect” by dragging fresh air into the tunnel from entry portal under a smooth traffic flow. The pollutant concentrations inside tunnel will be diluted by the fresh air and maintained within an acceptable level. However, under a congested scenario, the “piston effect” is significantly reduced while the pollutants emissions from the vehicle will be accumulated inside the tunnel. With reference to a recent tunnel project in Hong Kong, fresh air requirement for pollutant control and “piston effect” at various traffic speed are illustrated in figures.

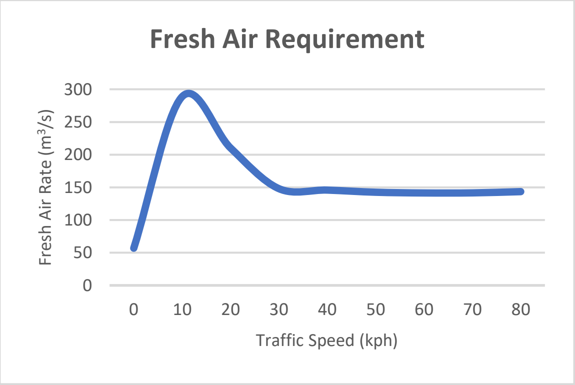


Figure 1: Fresh Air Requirement at various Traffic Speed

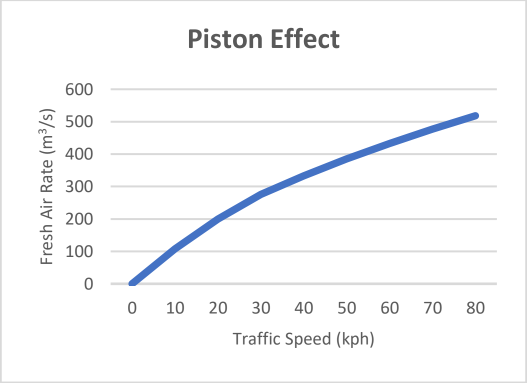


Figure 2: Piston Effect at various Traffic Speed

To achieve effective tunnel air quality control under various traffic flow, enhancement of the semi-transverse ventilation system operation with the "piston effect" is necessary.

2.4. Unbalance Air Flow Effect for Smoke Extraction

During a fire scenario, the tunnel ventilation system performs smoke extraction at the incident smoke zone through the Overhead Ventilation Duct (OHVD). Make-up air (i.e. fresh air introduced into the smoke zone to replace air removed by smoke extraction system) is naturally drawn from two tunnel portals at both sides. In certain cases when the fire locates closer to either end of the tunnel, more make-up airflow will be drawn from the closer end with high air velocity than that from another end. This would result in an unbalance amount of make-up airflow towards the fire site. Smoke layer may be disturbed by higher make-up air velocity and drops below the design smoke clear height faster, and thus tenable environment cannot be maintained on escape path. Figures below illustrate the adverse effect of unbalanced makeup airflow during smoke control.

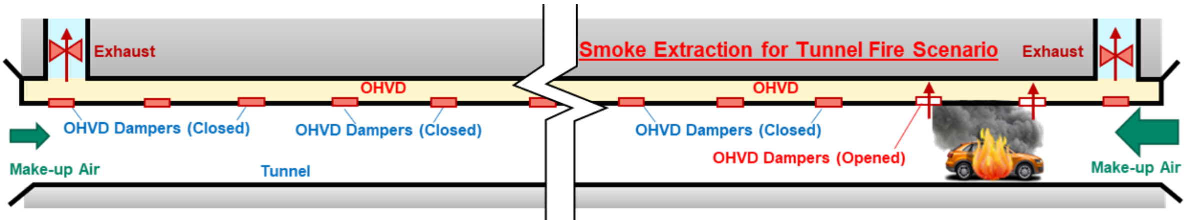


Figure 3: Unbalance Make-up Air for Tunnel Fire Scenario close to one Tunnel Portal during Smoke Extraction

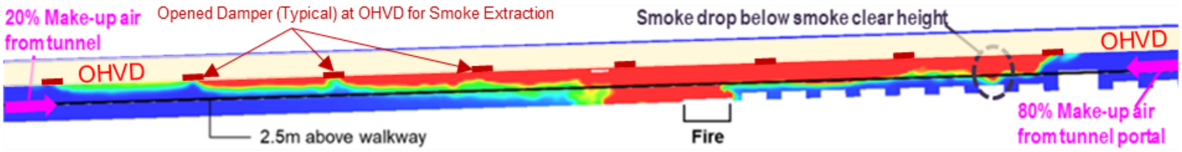


Figure 4: Computational Fluid Dynamic (CFD) Simulation reveals Smoke Drop below Smoke Clear Height due to Unbalance Make-up Air

3. STUDY OF FEASIBLE RESOLUTIONS FOR ENHANCEMENTS

3.1. Enhancement to suit Tunnel Geometry

For a 2-lane tunnel tube, ventilation points can be arranged in single (i.e. one ventilation point per tunnel cross-section) or double opening(s) (i.e. two ventilation points per tunnel cross-section) along the OHVD. For a 3-lane tunnel tube, the ventilation points would be better arranged with minimum double openings (i.e. two ventilation points per tunnel cross-section) along the OHVD for more evenly distributed smoke extraction performance. It is important to locate these ventilation points at high level so as to capture the smoke more effectively. As the smoke extraction rate is estimated based on design fire size against the design smoke clear height for escape path, the dimensions and distribution of the ventilation openings on the OHVD shall take account the effectiveness of smoke extraction. Therefore, “plug-hole” effect (“Plug-hole” effect occurs when the air velocity entering an extraction point is high enough to entrain clear air from below the smoke layer into the extraction point. The problem with “plug-hole” effect is that clear air will be extracted instead of smoke which resulting in reduction on effectiveness of smoke extraction system.) shall be carefully assessed and avoided with appropriate smoke extraction velocity passing through the ventilation point against depth of smoke layer below the point. To meet the design smoke extraction performance, more ventilation openings with smaller dimensions are required in some cases.

In some tunnel geometry, evacuation path or walkway is elevated (i.e. above road level). The design smoke clear height shall include this elevation to ensure a smoke clear path above the walkway for evacuation and firefighting uses. The smoke extraction rate and associated ventilation points of the semi-transverse tunnel ventilation system will be increased to meet performance requirement in this tunnel geometry.

3.2. Enhancement to tackle Gradient Effect

To evaluate vehicle emission of several common pollutants, PIARC has provided a comprehensive methodology regarding emissions of pollutants generated from the vehicles under various speed. This method also provides average emission factors for each pollutants accounting for associated gradient of the road where the vehicles are travelling on. These pollutants accumulate faster along the tunnel with longer uphill section towards downstream of the traffic. To maintain the pollutant concentration level within the maximum allowable limits throughout the tunnel, fresh air shall be supplied to the tunnel by two commonly used ventilation schemes:

(1) Constant rate along the tunnel to keep the pollutant concentration level under the design maximum allowable limits (refer to Figure 5), or;

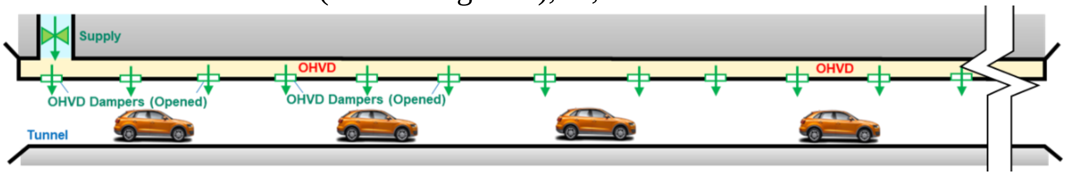


Figure 5: Evenly Distribution of Fresh Air Supply via OHVD Openings along tunnels

(2) Variable rate at dedicated location in tunnel that can bring down the pollutant concentration to certain level such that the subsequent “peaks” of the pollutant level remain under the design maximum allowable limits (refer to Figure 6).

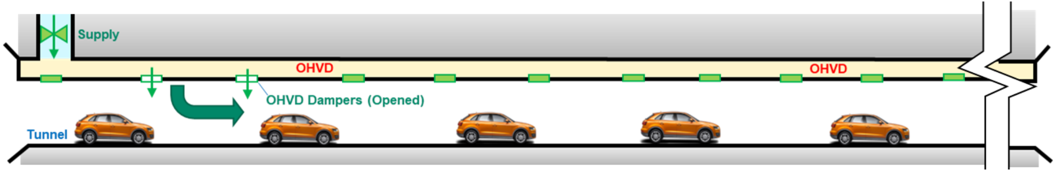


Figure 6: Variable Rate with Point Supply of Fresh Air Supply via OHVD Openings in tunnels

Table 1: Comparison of the two ventilation schemes

Factors of Comparison	**Constant rate along tunnel**	**Variable rate at dedicated location**
Balance of airflow at ventilation points	Airflow rate via majority of dampers on OHVD need to be balanced along tunnel	Airflow rate via dedicated zone(s) of dampers on OHVD need to be balanced
Number of dampers in operation	Majority of dampers on OHVD shall be open	Dedicated zones of dampers on OHVD shall be open
Flexibility for variation of gradient effect	Refinement of ventilation rate at each damper is required	Refinement of ventilation rate at dampers is not required
Flexibility for variation of traffic condition	Lower due to fixed setting of damper openings	Higher by adjustment of ventilation rates only

Furthermore, the design of semi-transverse ventilation system for smoke control involves more robust considerations to deal with the gradient effect. As the accumulation of smoke at higher side of the incident tunnel section is faster due to its buoyancy and therefore, this indicates a higher smoke extraction rate or smoke extraction density is required to maintain a design smoke clear height along the escape path. In another words, the same smoke extraction capacity shall be applied to a shorter tunnel smoke zone with higher gradient, while it is applied to a longer tunnel smoke zone with lower gradient. For various tunnel geometry and tunnel configurations, the required smoke extraction rate for different gradient section shall be verified or optimized by computer simulation analyses, for example, Subway Environment Simulation Programs (SES) and Computational Fluids Dynamic (CFD) simulation.

3.3. Enhancement to suit various Traffic Flow

Under the semi-transverse ventilation scheme, a Variable Supply Zone Method is recommended to tackle variation of the piston effect given from the change of traffic flow. This method is to provide fresh air supply via OHVD at specific supply zone in the tunnel at different traffic conditions. Change on piston effect due to different traffic conditions is monitored by airflow sensors installed in the tunnel. The specific supply zone will be activated corresponding to the airflow monitored by airflow sensors.

Considering a “weak” piston effect under congestion, fresh air is strategically supplied near the middle of the tunnel, such that the supplied fresh air dilutes pollutants and direct the airflow towards portals on both ends. When the piston effect increases with the traffic speed, majority of the supplied fresh air will be pushed by vehicle movement towards exit portal and the airflow rate travel towards entry portal will becomes less. In this case, the supply zone will be shifted towards to the entry portal such that the fresh air supply can ride on the piston effect to ventilate the tunnel. Each specific supply zone and its location corresponding to specific piston effect will be assessed by simulation analysis. The shifting of the supply zone on OHVD under different traffic flow conditions is illustrated in the Figures 7 to 9.

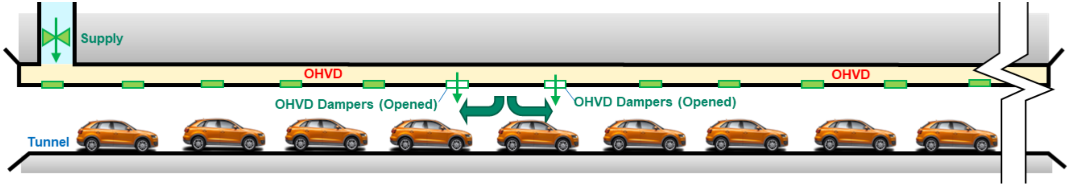


Figure 7: Zone Supply of Fresh Air Supply via OHVD Openings under Congested Traffic

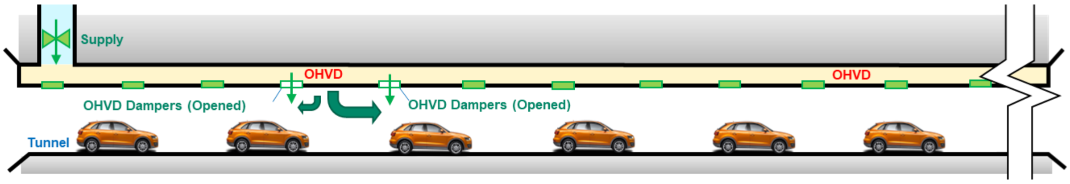


Figure 8: Zone Supply of Fresh Air Supply via OHVD Openings under Smooth Traffic

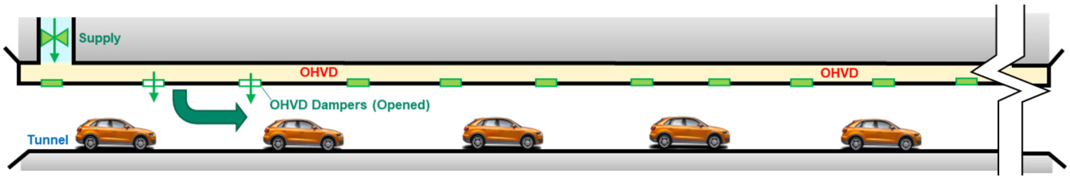


Figure 9: Zone Supply of Fresh Air Supply via OHVD Openings under High Traffic

The Variable Supply Zone Method can be adopted for changes of traffic condition as an effective ventilation strategy of the semi-transverse ventilation scheme. For a longer tunnel with larger aerodynamic resistance, the Method could be further enhanced with jet fans along the tunnel, and the jet fans can improve control of tunnel airflow by pushing towards to the exit portal regardless of traffic conditions (refer to Figure 10). Simulation analysis can be used to optimized distribution of supply airflow under various traffic speed.

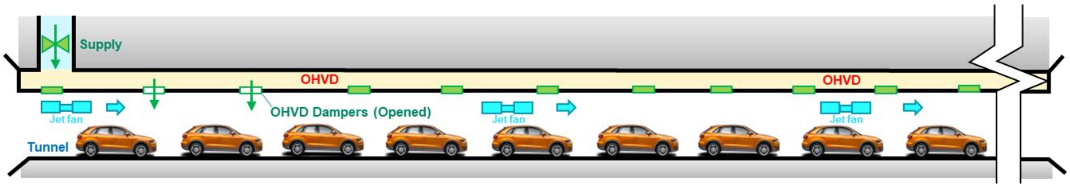


Figure 10: Zone Supply Method with Jet Fans for Fresh Air Supply via OHVD Openings

3.4. Enhancement to achieve a Balanced Makeup Airflow for Effective Smoke Control

As described in Section 2.4, the challenge of unbalanced natural markup airflow could cause ineffective smoke control with semi-transverse tunnel ventilation system. Taking a recent Hong Kong road tunnel project of approximate 3.2km long as an example, simulation analysis by using SES was performed to examine the natural make-up airflow rate on both sides of each smoke zone. SES results showed that a reasonable balance airflow effect could be obtained when the fire locates near the middle sections of the tunnel. The difference on make-up airflow quantity between two sides of the smoke zone increases when the fire location shifting towards tunnel portal on either side. The largest difference on make-up airflow between two sides of smoke zone (approx. 70% and 30% of natural make-up airflow from two sides respectively) happened when the fire site is located right next to a tunnel portal (refer to Figure 11).

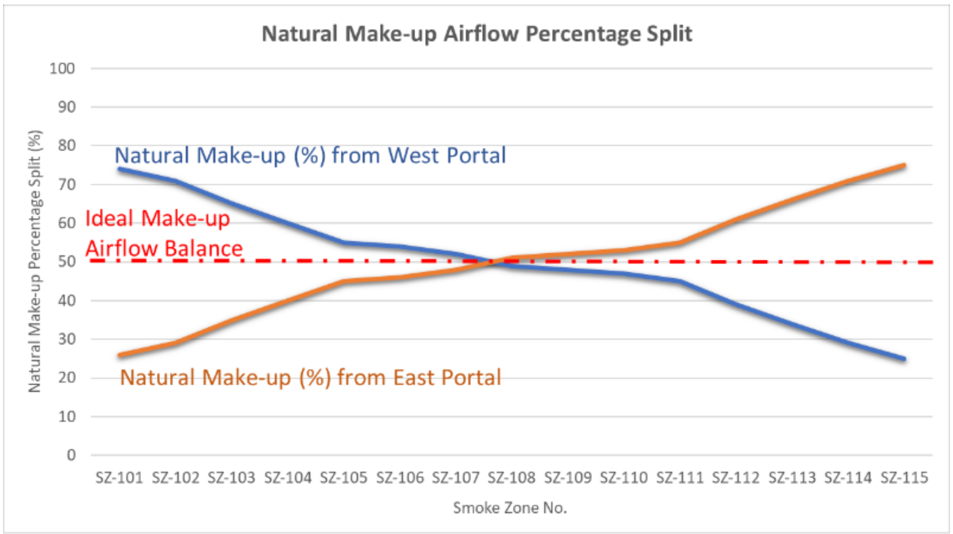


Figure 11: Natural Make-up Airflow Percentage Split

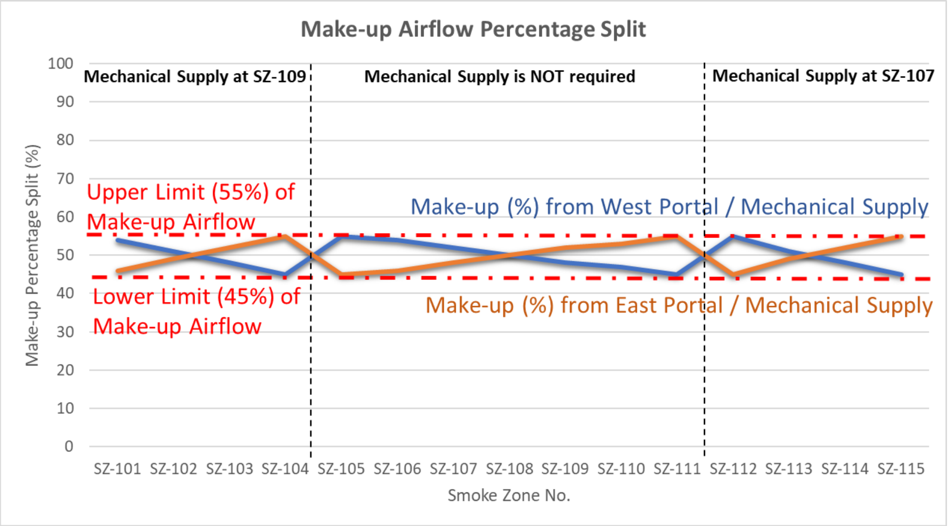


Figure 12: Make-up Airflow Percentage Split by Fixed Supply Zone Method

To enhance system operation for a balanced makeup airflow, a Fixed Supply Zone Method is implemented by air supply at dedicated vent zones with an acceptable range of make-up airflow in terms of percentage (for example, 45% - 55% split of make-up airflow from two ends). Simulation analysis shall be used to verify whether the range of makeup airflow split could result in design smoke clear height under the operation of smoke extraction system. The operation principle and ventilation zone arrangement are illustrated in the following Figure 13 for example. When the fire locates in zone A, B and C with smoke extraction system in operation, the mechanical make up air will be supplied on another end of tunnel at the fixed location (i.e. the fixed supply zone) with fixed supply make up airflow rate, so that 45% - 55% split of make-up airflow from two ends can be achieved. The graph in Figure 12 illustrates effective range of makeup airflow control for different locations of fire site where smoke extraction is performed.

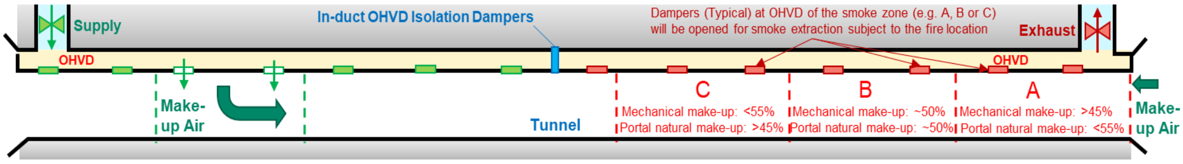


Figure 13: “Fixed Supply Zone Method” for smoke extraction and dedicated mechanical make-up air supply zone

This Method is successfully applied in the semi-transverse system design and operation for the recent road tunnel projects in Hong Kong. Result of CFD analysis in Figure 14 shows that tenable environment can be maintained by the smoke extraction system under the make-up airflow percentage split.

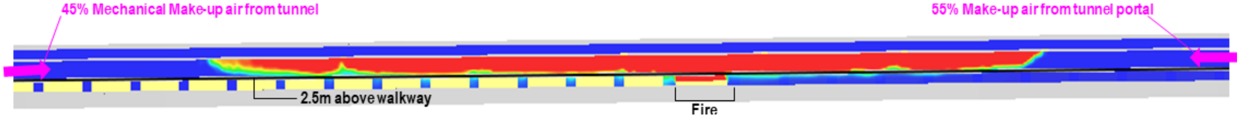


Figure 14: Computational Fluid Dynamic (CFD) Simulation reveals tenable environment can be achieved under a percentage split of 45% and 55% make-up airflow (CFD result from project reference)

4. TESTING OF TUNNEL AIRFLOW BALANCE CONTROL

4.1. Road Tunnel Test

This section presents the testing approach and results for a recent Hong Kong dual 2-lane road tunnel (approx. 4.8 km), focusing on fire-mode validation of the enhanced semi-transverse ventilation strategy adopting the “Fixed Zone Method” for mechanical make-up air. The installation comprises 24 tunnel ventilation fans (TVFs) rated at 85 m3/s across three Ventilation Buildings (VBs), connected to a reinforced concrete Over Head Ventilation Duct (OHVD) divided into two sections by a central dividing wall. Airflow distribution is controlled by 1,302 Motorized Fire and Smoke dampers (MFSDs).

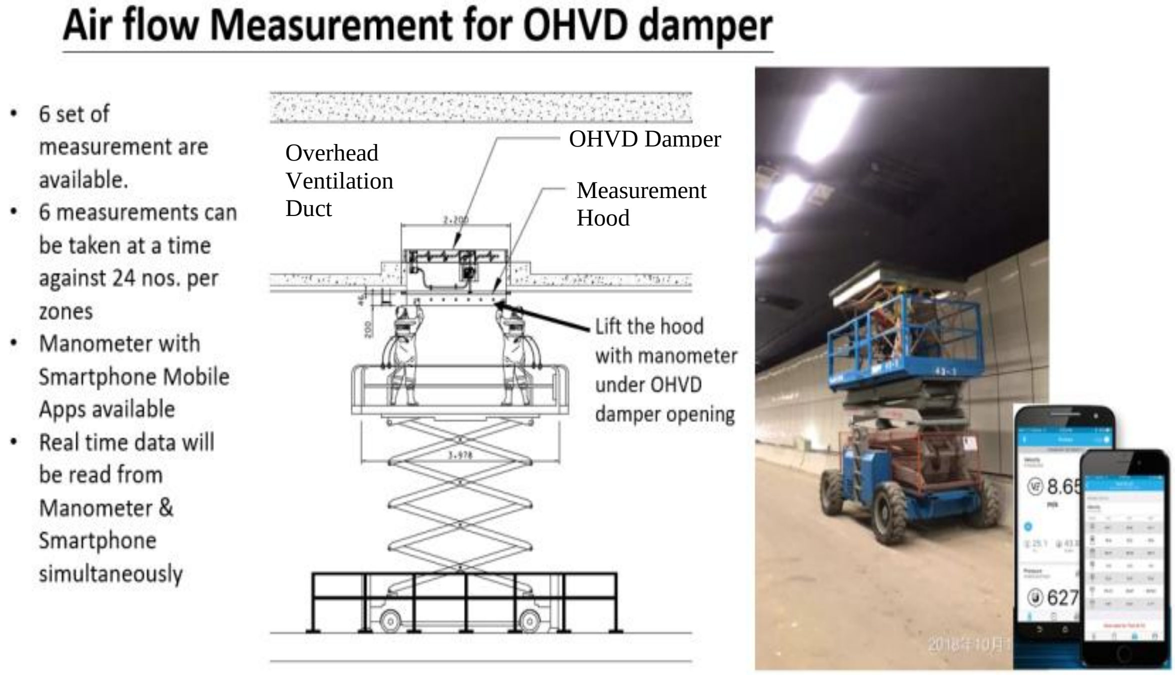
Two representative smoke extraction scenarios were selected for field validation against SES/CFD design predictions, and the target make-up split of approximately 45–55%: Z-009 at the middle of the tunnel with natural make up air and Z-016 close to the tunnel exist portal are selected to validate the assumption of make-up air flow percentage split (45%-55%) from each side of the smoke zone. Lanes closed, no traffic; ambient wind monitored; steady-state achieved before logging.

4.2. On-site Air flow Measurement

OHVD MFSDs total flows (extraction and supply): By using calibrated hot-wire anemometers across the MFSD free area. Where practical, a suitable flow hood and differential manometer were used for corroboration. To enhance the flow measurement efficiency in this scale of projects, 4 groups of technicians utilized synchronized wireless data capture technology to measure a single smoke extraction mode in approximately 20 to 30 minutes. The precise time required varied based on the specific count of dampers within the active zone being tested.

Tunnel make-up airflow approaching the active smoke zone will be simultaneous multi-point velocity measurements, performed at 2 sections located about 10m upstream and 10m downstream from the active extraction zone, using hot-wire anemometers with synchronized logging at steady state. This gives the result of section-average velocity, volumetric flow rate (using surveyed cross-sectional area, and the percentage split of total make-up air from each side of the smoke zone.

Summary of Tunnel Airflow Measurement Results of Two Smoke Zones – Z009 and Z016 is illustrated in the table below. The summary aims to show the comparison between make up split predicted during design and actual measured data.



Air flow Measurement for OHVD damper

- 6 set of measurement are available.
- 6 measurements can be taken at a time against 24 nos. per zones
- Manometer with Smartphone Mobile Apps available
- Real time data will be read from Manometer & Smartphone simultaneously

Figure 15: Air flow measurement for OHVD damper

Table 2: Actual Site Measurement

Smoke Zone No.	Total Extraction capacity	Make up air flow			
		Upstream		Downstream	
		Design	Actual	Design	Actual
Z009	323.49 m^3/s	Natural make up Split %: 41.9%	Natural make up Split %: **46.0%**	Natural make up Split %: 58.1%	Natural make up Split %: **54.0%**
Z016	348.91 m^3/s	Mechanical Make Up Split %: 41.7%	Mechanical Make Up Split %: **40.2%**	Natural make up Split %: 58.3%	Natural make up Split %: **59.8%**

4.3. Airflow Control Effectiveness

Results of tunnel airflow tests closely matched SES/CFD predictions and validated the Fixed Zone Method for smoke-mode operation in semi-transverse ventilation. For the mid-tunnel case (Z009) demonstrated balanced natural make-up without mechanical supply. On the other hand, the near-portal case (Z016) confirmed that a dedicated fixed mechanical make-up zone on the far side reliably delivers a balanced make-up split within the 45–55% acceptance range, supporting smoke layer stability and clear height targets for evacuation.

The adopted field methodology—Building Services Research and Information Association (BSRIA)-based MFSD face flow traverses plus simultaneous upstream/downstream section measurements—provided repeatable, efficient verification of extraction capacity and make-up split, enabling direct comparison with SES/CFD outputs and confirming the robustness and operational simplicity of the enhanced control strategy.

5. REAL-TIME AUTOMATIC SYSTEM CONTROL AND MONITORING

5.1. Centralized Monitoring & Control System

To achieve a real-time automation of the tunnel ventilation system, control and monitoring functions could be formed as a dedicated standalone system (i.e. Tunnel Ventilation Control System – TVCS) or integrated with a Centralized Monitoring & Control System (CMCS), which performs multi-system interface and operational control functions. The system involves several major sub-systems as below:

(1) Tunnel Ventilation Control System (TVCS) – for determining operation modes to be activated based on signal/data received from other sub-systems and control the operation of all elements of the system such as fans (e.g. on/off/speed-control of fan-group or individual operation) and dampers (zonal/individual operation), etc.

(2) Air Quality Monitoring System (AQMS) – for monitoring of the tunnel air quality such as pollutant levels, airflow velocity and visibility, etc.

(3) Fire Detection and Alarm System – for detection of fire/heat/smoke in tunnel and generating alarm signal to associated systems (including tunnel ventilation system)

(4) Traffic Control & Surveillance System (TCSS) – for generating of traffic control signals during normal and emergency operation scenarios

5.2. Automatic Control under Normal Operation

During normal operation, pollutants' level and visibility along the tunnel are two major factors determine the tunnel ventilation requirement. Real-time measurement is carried out by the AQMS regarding concentration of CO, NO_x and visibility/PM level at critical locations along the tunnel, which are fed into the TVCS to check against the threshold limits of these factors. When any one of these factors is reaching an associated preset value, level-up operation of the tunnel ventilation system will be triggered by increasing speed or number of fans in operation to supply more fresh air into the tunnel and bring down the value(s) to an acceptable level. The control logic is the same but in reverse fan control for level-down operation, the speed or number of fans will be reduced when the factors are lower than preset values. This is a closed-loop automatic control method for the real-time control and monitoring functions which aim at energy-saving and cost-effective operation of the tunnel ventilation system.

In the enhanced semi-transverse tunnel ventilation system, locations of the AQMS sensors are essential to take account various traffic operations and conditions. For example, in a smooth un-directional traffic condition, higher "piston effect" will generate higher airflow velocity and the peak of the pollutant level along the tunnel is commonly close to the exit portal. However, during a congested traffic, the peak is likely shifted to the middle of the tunnel due to lower "piston effect" (i.e. lower tunnel airflow velocity). As such, tunnel sensors can be installed in closer interval so as to pick up the tunnel environmental conditions along the tunnel closely in order to for the TVCS to select the most appropriate operation mode as described in section 3.3 of this paper.

5.3. Automatic Control under Fire Emergency Operation

In case a fire accident occurring in a tunnel, location of the fire site shall be firstly identified by the tunnel fire detection and alarm system (e.g. linear heat detection system or heat/smoke detection system) with a corresponding smoke/vent zone(s). The associated signal of the fire location will then be sent to the TVCS and TCSS for verification, if necessary. Based on location of the incident smoke zone, a predefined emergency mode of the tunnel ventilation system shall be selected automatically by TVCS to actuate a TVS operation. As an enhanced smoke control strategy, suitable amount of mechanical makeup air will be supplied to the incident tunnel via a well-defined location/zone so as to facilitate an effective smoke control operation as explained in Section 3.4 of this paper.

At the same time, the tunnel fire alarm will also be triggered to actuate planned tunnel fire services (e.g. fire hydrant system and alarm/exit sign at cross-passages) as well as directly report the fire incident to the associated fire service departments. Moreover, the fire information could be sent to TCSS for further traffic control along the incident tunnel. For example, TCSS could set up traffic control signs to direct those vehicles at downstream of the fire site out of the tunnel and to stop those vehicles at upstream of the fire site from moving toward the incident location.

5.4. Potential Application of Internet-of-Things (IoT) and Digital Twin Technologies

Following advancement of technology, more comprehensive tunnel, traffic and even atmospheric data could be monitored and integrated into the control system via IoT and digital twin technologies. Some potential innovative considerations are listed for further exploration:

(1) **Real-time traffic throughput and mix data** – Traffic flowrate and types of vehicles at entrance of a tunnel could be used to estimate changes of “piston effect” and pollutant emissions along the tunnel. If these data could be collected via TCSS and evaluated by TVCS in advance, more closely tracked tunnel ventilation capacity and mode operation could be actuated in advance to minimize gap of lead-lag condition between monitoring and control of the tunnel ventilation system.

(2) **Corelation among background air quality, tunnel air quality and portal emission** – Pollutants’ concentration level in atmosphere is one of factors determine the fresh air requirement for the tunnels. The pollutants’ concentration level will be built up along the tunnel and the air mixtures will be discharged back to the outside ambient in return. Real-time monitoring of the pollutants’ concentration levels in these three entities could effectively evaluate not only the tunnel ventilation capacity but also the portal exhaust capacity, if portal emission control is necessary, based on the actual pollutants level for a cost-effective system operation.

(3) **Enhancement of monitoring and control of mechanical makeup for effective smoke control** – Referring to the enhanced smoke control strategy in Section 3.4, bi-directional airflow velocity measuring sensors can be installed in tunnel section near both portals. These sensors can carry out real-time monitoring of the markup airflow rates from both sides of the fire site, and the data could be fed into the TVCS to control the make-up fan capacity in order to achieve a relative balanced makeup airflow pattern to improve the smoke control performance.

With advancement of IoT to integrate connections among multiple data, which could be used in a digital twin model of the tunnel systems, it is anticipated that the tunnel operation could be more efficient and cost-effective in dealing with various conditions.

6. SUMMARY

For the commonly used semi-transverse tunnel ventilation scheme, the paper has identified major critical elements that may affect the operational effectiveness and efficiency of the associated tunnel ventilation system including tunnel geometry and alignment, traffic operation and unbalanced natural make-up in smoke control. Potential resolutions for these critical elements have been elaborated in detail with project reference of computer simulation analysis and on-site tunnel airflow test for illustration. Last but not the least, innovative ideas about real-time automatic system control and monitoring based on more comprehensive tunnel and traffic data collection are introduced riding on the advancement of IoT technology. These ideas could be further investigated and developed for implementation in future tunnel projects.

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