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Transverse ventilation system applied to unidirectional road tunnel: Practical case of S2 Tunnel in Warsaw

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ABSTRACT: This paper concerns a practical case of transversal ventilation system applied to a unidirectional road tunnel and how the functional design has enabled the optimization of the tunnel geometry, reducing the estimated implementation costs and thereby promoting the award of the Contract with the subsequent realization of the works. The ventilation system described is related to the twin-tube tunnel (2.4 km long) located on the new roadway S2-Southern Bypass in Warsaw – Task A. It is then described the starting assumption about the performance of the ventilation system, the draft presented by the Contracting Authority during the tender phase and the optimization proposals, these last ones as results of the analysis of the required performances. Furthermore, It has been demonstrated the applicability and effectiveness of the Computational Fluid Dynamics (CFD) and the Fire Safety Engineering for the validation of the transversal ventilation system in a road tunnel with unidirectional traffic.

1 INTRODUCTION

Generally, ventilation system has an important impact in the main geometry and functionality design of a road tunnel. Interferences increase especially when it comes to transverse ventilation and where additional ventilation ducts or chambers installations are usually required.

The scope of this paper is to show how a careful optimization of ventilation system design can lead towards new technical solutions that reduce impact on civil works. In particular, in the case of the WARSAW SOUTHERN BYPASS S2 TUNNEL Project, the use and application of a new design configuration allowed the optimization of the tunnel geometries by restricting the excavation sections and consequently reducing the cost analysis; this allowed, during the tender phase, the awarding of the works to the contractor.

The innovative design solutions have been verified, in terms of efficiency and reliability, during the design building permit design using the Computational Fluid Dynamics and Fire Safety Engineering Techniques.

2 TENDER REQUIREMENTS

2.1 *Technical e geometrical data*

The functional elements of S2 road tunnel (as prescribed by Tender Functional-Utility Program) are fixed for every tube:

– traffic lanes: 3 × 3.50 m
– emergency lane: 1 × 3.75 m
– roadsides: 1 × 0.25 m
– sidewalk: 2 × 1.0 m
– nominal speed (traffic): 80 km/h
– gauge (height): 4.70 m
– transversal slope (road): 2.5% (min.).

All the functional elements were annexed to a unique cross section inside tender project as reported below.

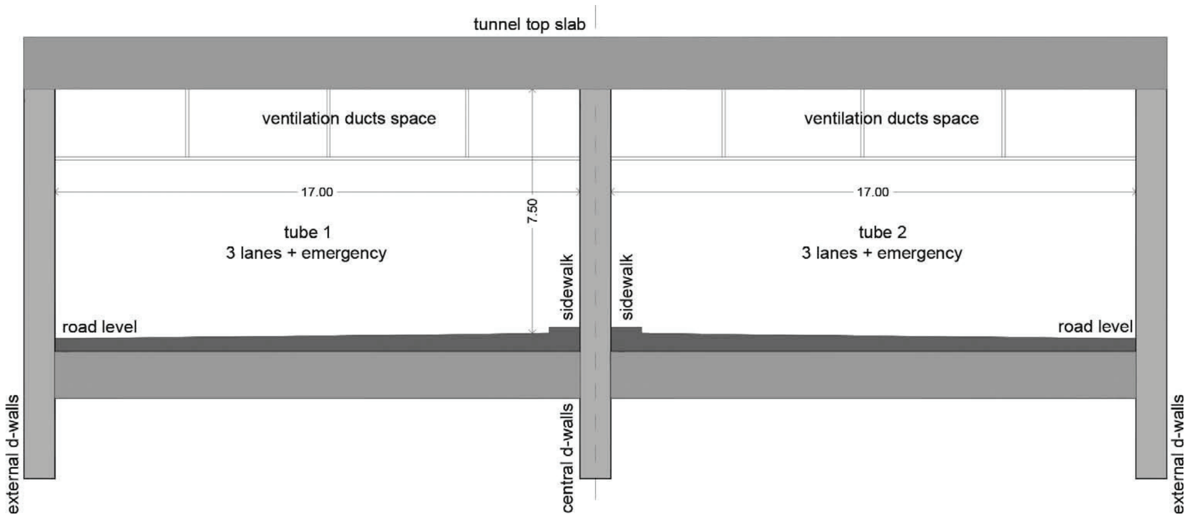

Figure 1. Typical cross section with main ventilation elements.

2.2 *Ventilation system*

About ventilation system performances, mandatory requirements expressed by Regulation nr. 63 art. 735 of the Ministry of Transport and Polish Maritime economy, foresaw the use of transversal ventilation in the tunnel.

In fact, unlike what is required by the legislation of the other EU member states and the technical reference literature (see for example PIARC and RABT), the Polish law provides for the application of transverse ventilation systems in all road tunnels longer than 1000 m without distinction between functional and traffic types (one-way or two-way tunnels). Some basic elements of transverse ventilation were already contained in the tunnel concept design in which the use of a channel at the top of each tube was described to indicate the presence of one or more ventilation ducts.

According to the main reference manuals and guidelines for road safety design, such as the German RABT 2006 (Table 1), transverse ventilation should be applied mainly to two-way traffic tunnels longer than 1000–1500 m while it could be applied to unidirectional traffic tunnel with a length of over 3000 m, only when the results of the risk analysis (in terms of expected damage) do not give sufficient results just with the simple application of a longitudinal system.

Hence the main problem of colliding the regulatory and contractual requirements with tested and approved methods that do not provide the application of transverse ventilation in one-way traffic tunnels. In these tunnels, in fact, the main velocity component of the ventilation flow has longitudinal direction and is mainly produced by the presence of the circulating traffic and the related piston effect. A transverse system, to be defined as such, must be able to cancel the longitudinal component of the airflow velocity and create by itself a main transverse flow to the tunnel axis.

Table 1. Comparison between RABT and Polish law requirements.

Regulation - Guidelines	Tunnel length	Two-way tunnels	Unidirectional tunnels
RABT 2006	< 400 m	Natural ventilation	Natural ventilation
	400 – 600 m	Longitudinal ventilation	
		Risk analysis method: - Longitudinal	
	600 – 1200 m	- Longitud. intermediate shaft	Longitudinal ventilation
		- Semitransverse	
	1200 – 3000 m		
	> 3000 m	- Semitransverse ventilation - Fully transverse ventilation	- Longitud. intermediate shaft - Semitransverse ventilation
Polish Law nr. 63 poz. 735	< 1000 m	Longitudinal ventilation	
	> 1000 m	Transverse ventilation	

3 FIRST TENDER HYPOTHESIS

A first project idea was identified in the tender phase assuming a new geometry that included the two tunnel tubes separated by two ventilation ducts for air supply and exhaust. The solution seemed immediately winning as it allowed a strong reduction of the excavation sections and reduced the d-walls sizing.

In the first instance (Figure 2), it was decided to create a semi-transversal system with un upper exhaust duct and with a lower exodus path (escape tunnel) installed between two central

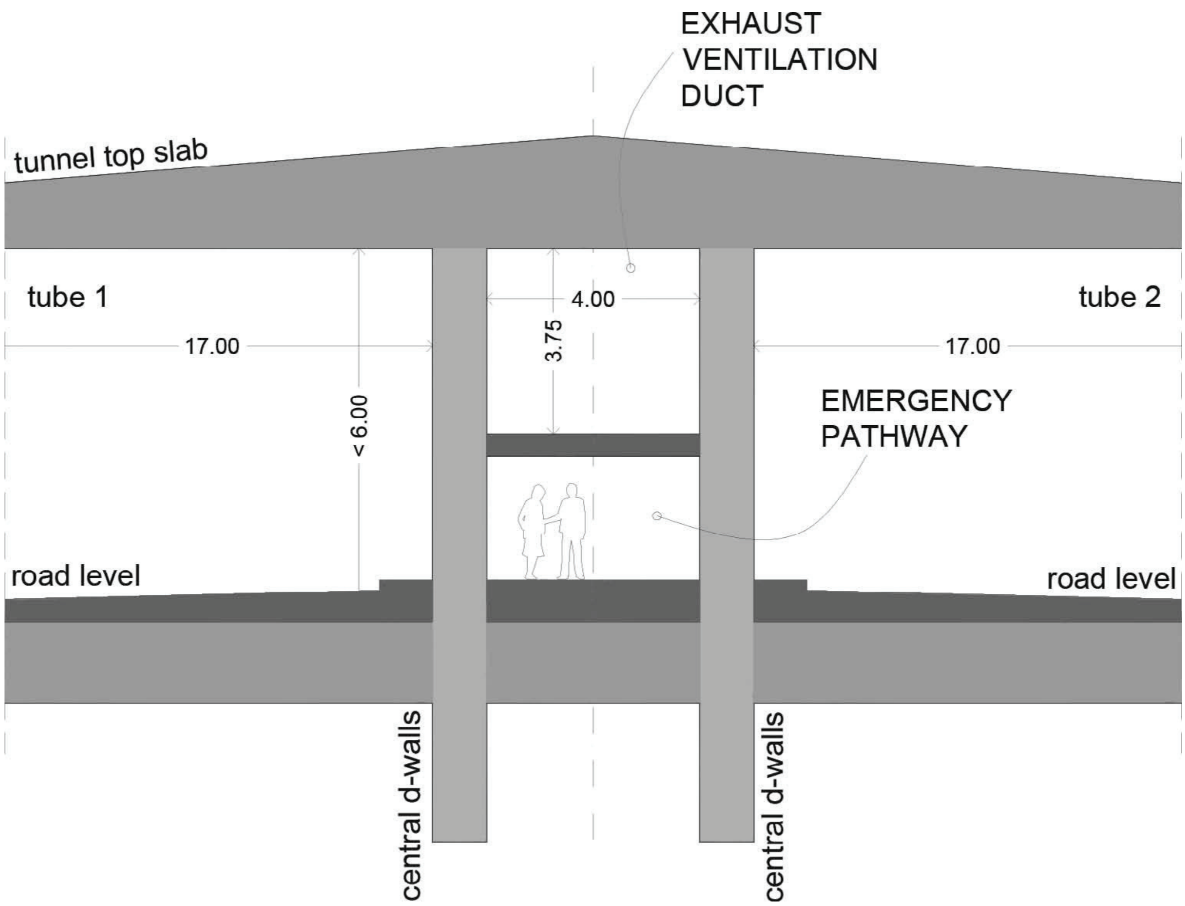

Figure 2. First solution provided in tender phase.

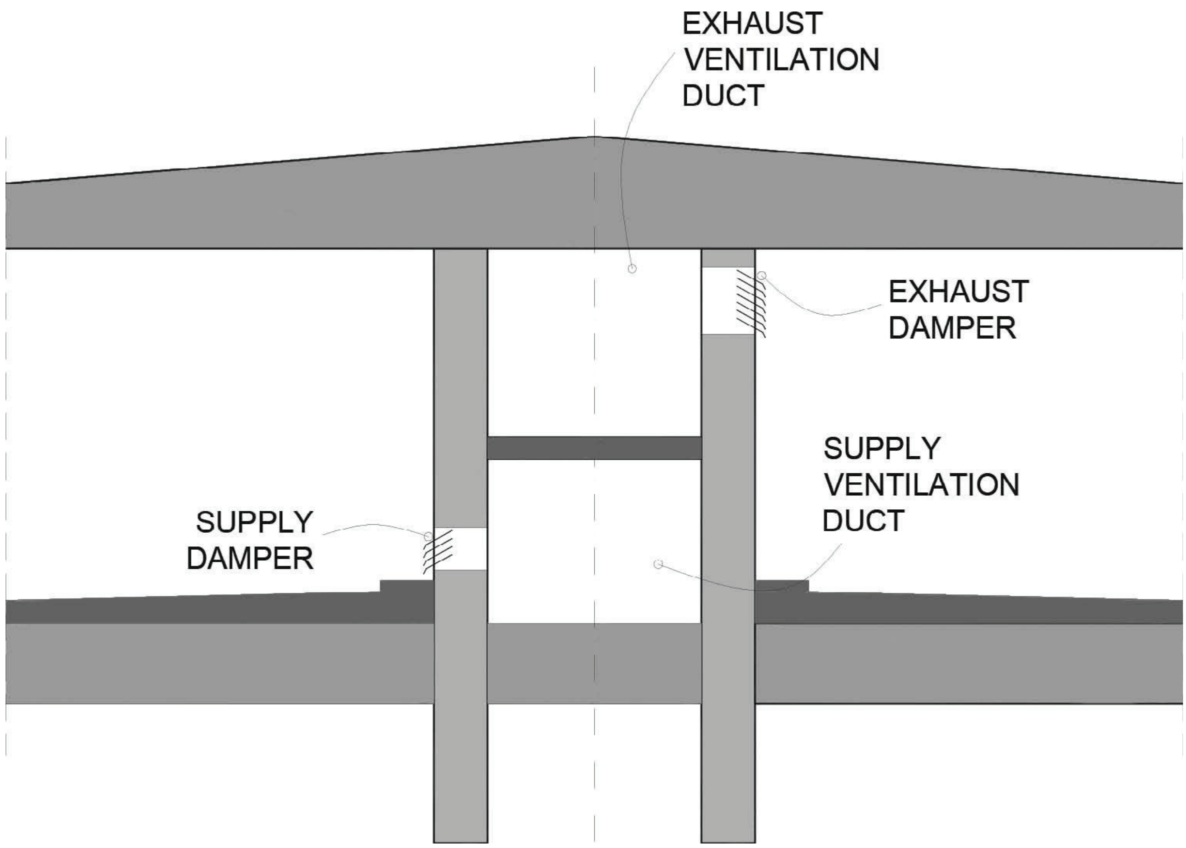

Figure 3. Final design solution provided in tender phase.

structural diaphragms. The proposal was shared as the best possible solution in terms of safety and efficiency of operation while ensuring the presence of a transversal system in the tunnel.

The mandatory necessity to create a purely transverse system (not semi-transverse – only with exhaust duct) then guided the Competitor towards the definitive design solution (Figure 3) which provides for the expansion of the escape tunnel and the relative replacement with a real own air supply duct channel.

The creation of a single pair of ventilation ducts to service both tunnel tubes, installed on the middle position between two road carriageways, has allowed a significant reduction in the estimated costs of construction without introducing any defects in efficiency and safety, thus ensuring the awarding final contract.

The final tender solution provided for a total of:

- the reduction of excavation volumes of around 300 000 m^3
- raising the level of the road with a total reduction in the excavation depth of approx. 2.00 m
- the construction of only two ventilation ducts common to the both tunnel tubes, together with the elimination of the false ceilings inside the tunnel.

With regard to the removal of the false ceilings, the constructive optimizations introduced during the design phase determined in any case the need to keep the top slab at the same original level provided by concept design and to create an intermediate closing slab in some sections. thus the double function of limiting the height of the traffic compartment and containing the deformations of the diaphragms.

4 VENTILATION SYSTEM DESIGN

The new S2 Tunnel transverse ventilation system consists essentially of a pair of rectangular ducts (13–15 m^2 net section) for the supply and extraction of air from the tubes (whose cross-sections are now equal to 110 m^2). Ventilation airflows are powered by a couple of ventilation station installed above the track, on the tunnel slab, in the technological and dedicated areas near the portals.

The air is supplied and extracted from the tunnel by means of motorized steel fire dampers (600 °C – 2h resistance) installed inside with 50 m spacing. Exhaust dampers have a total unit area of 5 m^2 and are installed in the upper part of the central diaphragms, while the supply dampers with 1.5 m^2 of unit area are installed in the lower level of the diaphragms, just above the road platform (Figure 4).

The ventilation system has been sized to guarantee the correct dilution of the pollutants produced by the vehicular traffic present in the tunnel in all the operating scenarios, contemplated in the traffic forecasting study, and at the same time, guarantee the management of those critical scenarios that foresee, the presence of congested or blocked traffic. Not only that, the system must guarantee, as required by the ventilation systems, the control of heat and smoke produced by a hypothetical event of fire in the tunnel, ensuring the safety and exodus of the involved users. At the scope to ensure compliance with the performance requirements and to validate the proposed ventilation model, during the tender phase and building permit design, Computational Fluid Dynamics (CFD) and the Fire Safety Engineering approach was used by performing the related fire simulations in the tunnel. The simulations were conducted in the hypothesis that an outbreak of fire with total heat release of 100 MW is present along the tunnel route. Fire scenarios and CFD simulations were performed ensuring the analysis of the "worst" locations keeping into account, among the others, the road slope level. In particular, as shown in Figure 5, simulations related to both ascend and descend tunnel section were performed – Fire 1 and Fire 2 scenarios.

The use of 100 MW fire with total smoke production equal to 200 m^3/s, is a very hard test for the verification of ventilation ducts, their sizing and relative spacing of the dampers as well as for the overall effectiveness of the ventilation station.

The innovative geometric and functional approach of the ventilation adopted for the tunnel suggested the completion of the study analysis extending the CFD approach, firstly required only for the analysis of the fire scenarios, also to the sanitary ventilation phases. So, new analysis were conducted in presence of critical operating scenarios with highly congested and/or jammed traffic in order to verify the effectiveness of pollutants dilution along the entire cross-section of the tunnel.

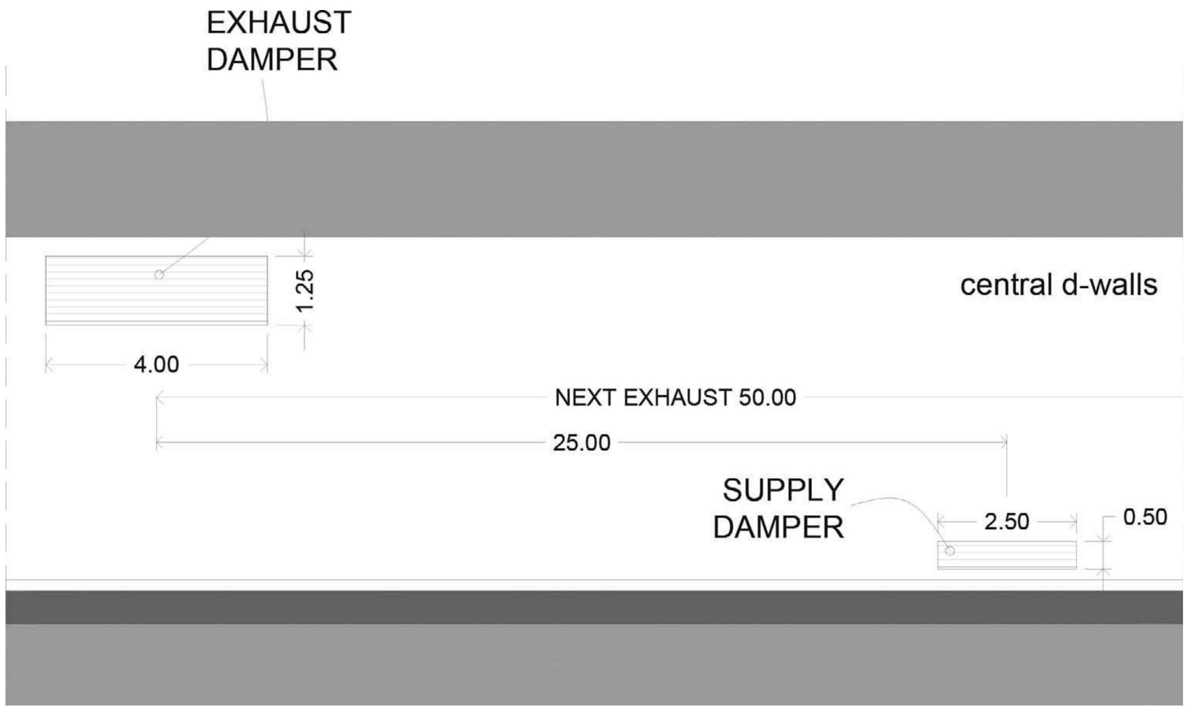

Figure 4. Transversal tunnel section (view of the central d-walls).

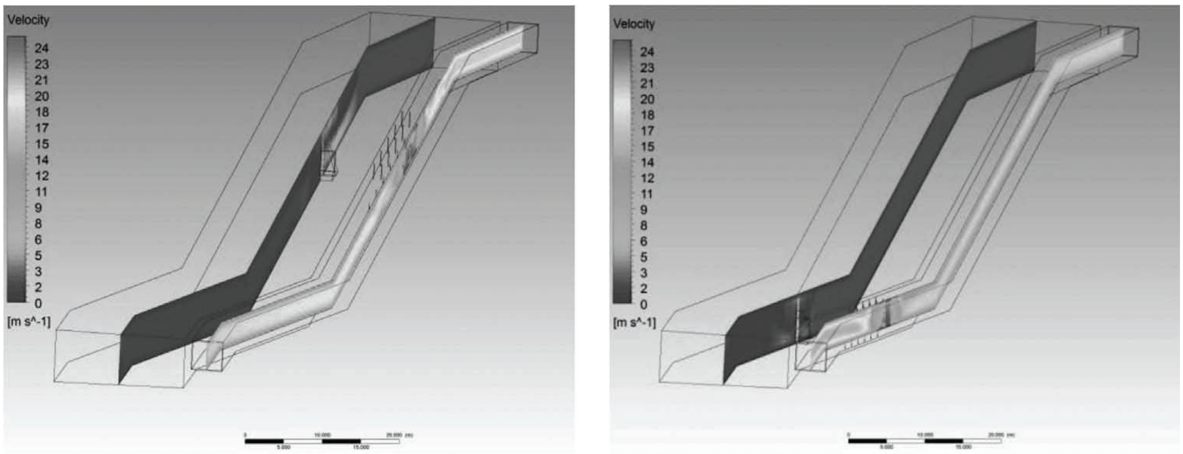

Figure 5. Fire 1 and Fire 2 velocity result (tunnel and exhaust duct).

5 CFD RESULTS

The results obtained by means of CFD analysis confirmed the correctness of the proposed solution both for tunnel sanitary and fire scenarios.

In particular, for the sanitary scenarios, the results have provided the expected pollutant dilutions confirming the effectiveness of the cleaning effect over the entire cross section of the tunnel. Specifically, as shown in Figures 6 and 7, the results the capacity of the system with overlying channels and vertical dampers to operate the full ventilation of the tunnel section from the central diaphragms up to the opposite side of the carriageway.

During fire events, for all the analyzed scenarios, the results showed the correctness of the proposed solution and allowed positive evaluations regarding the effectiveness of the ventilation. In particular, they highlighted the full capacity of the ventilation system to operate control of fire events with total heat release up to 100 MW and 200 m^3/s smoke production, with particular regard to the ability to extract smoke from tunnel and maintain tenability criteria (temperature pollutants and visibility) along the walkways and the emergency paths. For this aim, in the next figure FIRE 1 simulation results related to time step 500 s from the fire start are fully shown.

In particular you can see how temperature and visibility contours highlight the free smoke area in the lower layer above the road level; velocity contours show how 5 active dampers are working in the fire zone by extracting and removing smoke by the carriageway.

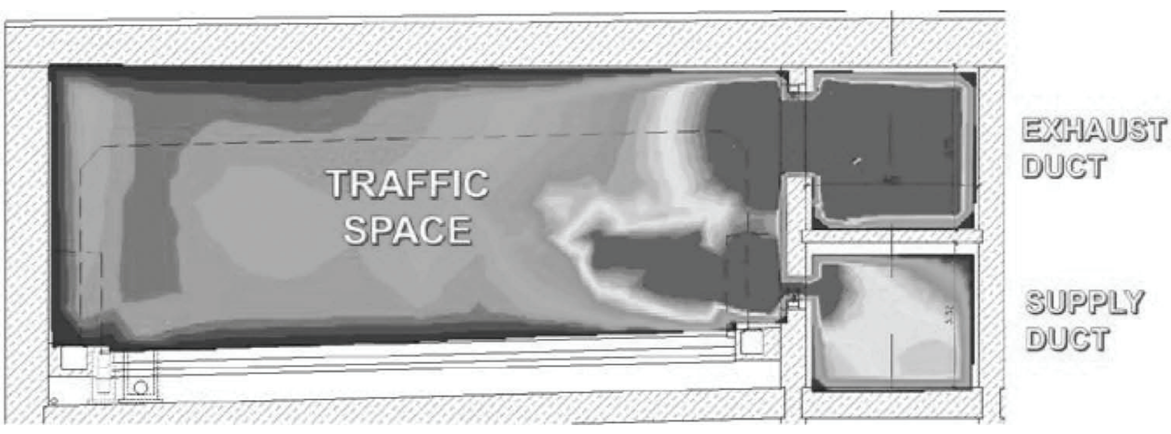

Figure 6. CFD Sanitary model result. Colored contours on a transversal slice section of air velocity - scale 0 (blue) – 5 m/s (red).

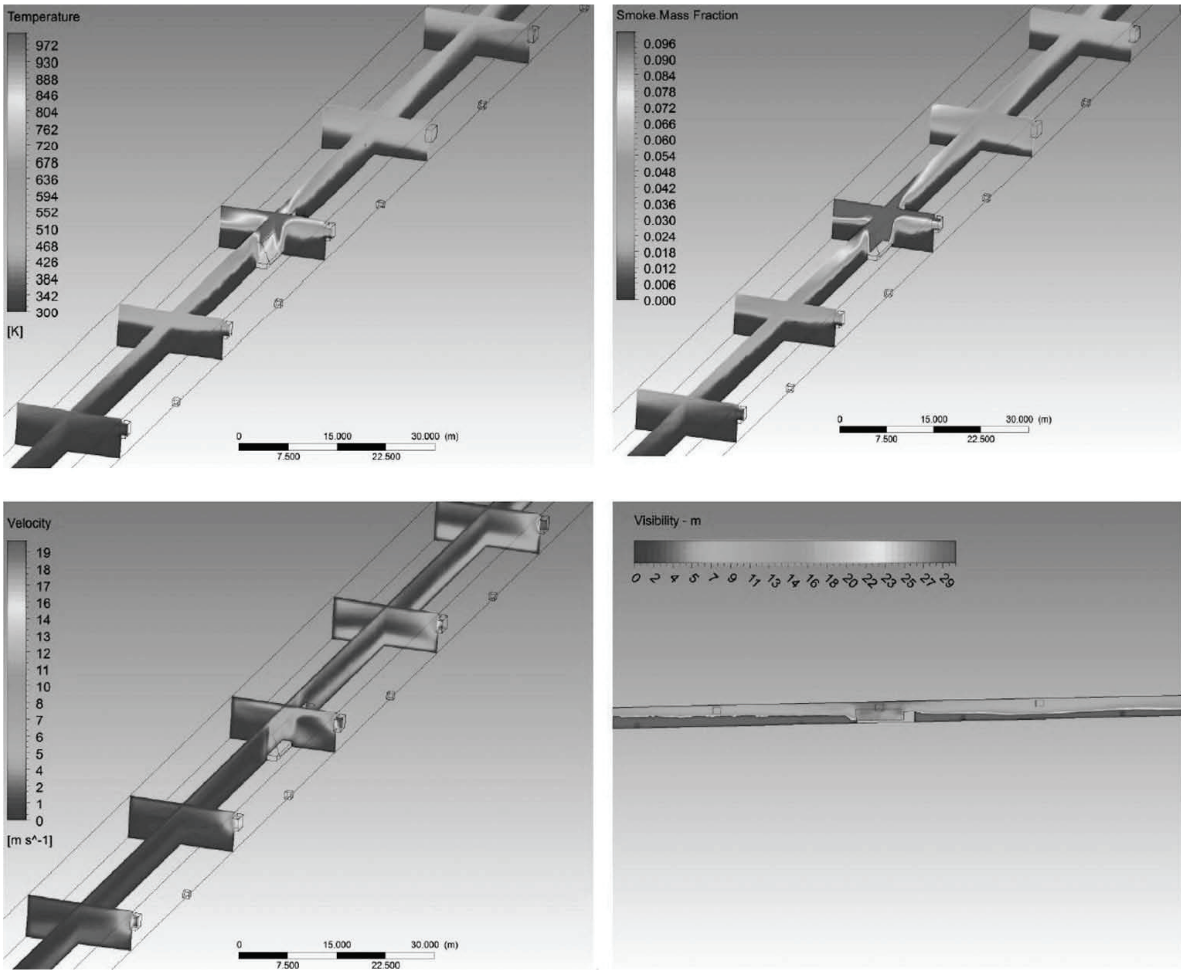

Figure 7. CFD fire model results. Colored contours of temperatures, smoke concentrations, velocity and visibility.

6 FINAL DESIGN

The fluid-dynamic analysis allowed also to determine the correct extraction capacity of the ventilation system and to make any necessary adjustments related to the presence of a vertical duct exhaust system. Furthermore comparative case studies are available in technical literature concerning positioning of ventilation dampers and louvers and they give some important advices about ventilation system behavior and their efficiency in presence of horizontal, vertical and inclined damper openings.

RABT 2006 and other technical guidelines suggest, for traditional transversal ventilation systems, to adopt an exhaust flow rate at least equal to one and a half times the smoke flow rate (reference fire scenario). This assumption should lead to choice a total extraction flow rate of 300 m^3/s but considering lower efficiency of exhaust system due to the presence of vertical dampers (instead of horizontal), the extraction capacity of the system has been increased by more than 30% and set up to 400 m^3/s.

Overall, tunnel transverse ventilation design includes:

- structural geometric configuration as proposed during the tender phase
- nominal exhaust flow rate equal to 400 m^3/s (huge!)
- nominal air supply capacity equal to 100 m^3/s
- transverse ventilation working along the entire length of the tunnel during sanitary ventilation scenarios
- transverse ventilation working just on the outbreak of fire tunnel area (sector operation) during fire ventilation scenarios.

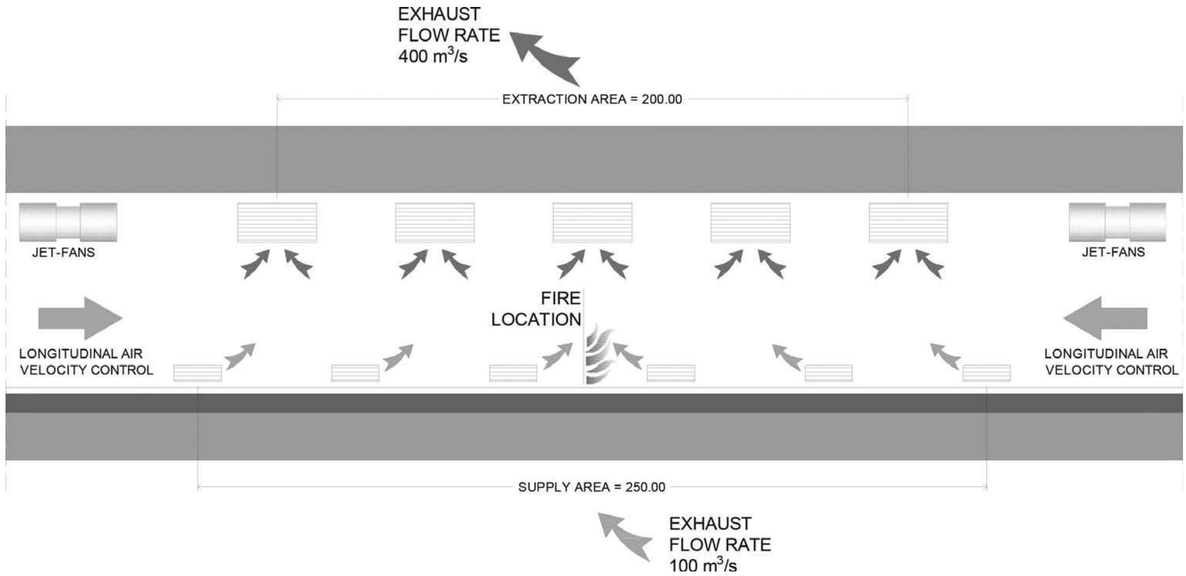

Figure 8. Nominal design flow rates.

Sector operation strategy during fire scenarios allows in fact to contain the extension of the tunnel area invaded by the smoke ensuring sufficient visibility along the exodus paths. Operating an extraction located just in the fire area also allows not to disperse the total exhaust capacity along tunnel area not affected by smoke. However, to take into account the leakage losses induced along the duct by the presence of non-operating dampers, during fire scenarios, the final design exhaust flow rate was further increased by 5% fixing total nominal performances of ventilation stations to 420 m^3/s.

7 JET-FANS AND VELOCITY CONTROL

In order to maximize the effectiveness of the transverse ventilation system, a series of jet-fans have been provided in the tunnel; jet-fans task is to keep controller the longitudinal velocity of the residual ventilation air flow. Air velocity control is required for both sanitary and fire ventilation scenarios and it is necessary to balance the overpressure produced inside tunnel by piston effect and meteo-climatic conditions. During sanitary mode, longitudinal air velocity control prevents the pollutants propagation in the longitudinal direction by reducing the part not extracted from the ventilation system and the consequent emission to the environment (from the portals).

In the event of a fire, the longitudinal speed control ensures maximum efficiency on smoke extraction operation. Ventilation control must ensure, in the fire zone, the presence of a

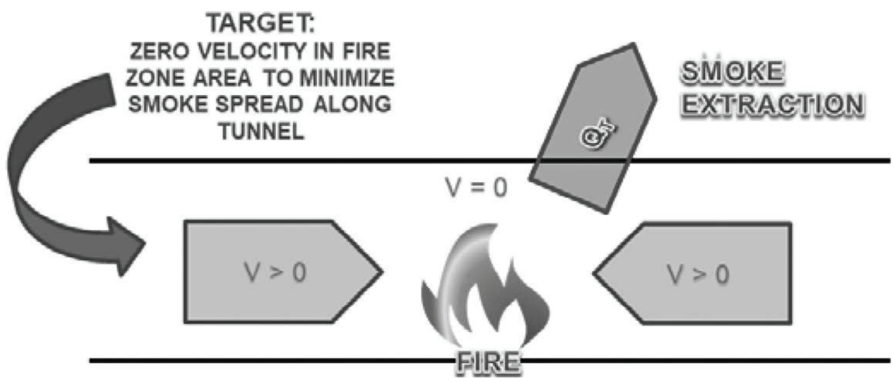

Figure 9. Flow rate balancing and Fire Ventilation strategy.

Figure 10. Smoke stratification and lower free smoke layer.

(quite) zero longitudinal velocity obtained as a natural balancing of the involved ventilation flows. The sum of the ventilation flows upstream and downstream of the fire, controlled by the installed jet-fans, must be equal to the total exhaust flow rate fixed in the fire zone according to the following scheme.

Longitudinal velocity control during the first stages of a fire event also ensures that the natural smoke stratification induced by fire is maintained as long as possible in its upper layer. Smoke stratification (Figure 10) is a basic phenomenon that assumes a main role in fire protection and fire-fighting operations. The buoyancy thrusts induced by fire can generate a warm layer (upper layer) which is self-supporting in contact with the tunnel ceiling and allows the coexistence of a lower free smoke area (lower layer) that assumes a primary scope in the users exodus capability.

8 CONCLUSIONS

In the practical case described above, applicability and efficacy of a transverse ventilation system to a unidirectional road tunnel has been demonstrated and verified. The performance approach by means of Computational Fluid Dynamics (CFD) and Fire Safety Engineering allowed ventilation system design optimization confirming the design choices made during the first design phases.

Simulations showed that the new ventilation system proposed is adequate, in all the tested operating conditions, to ensure:

- sanitary air exchange during normal and peak traffic scenario
- smoke extraction and temperature control during fire scenarios.

REFERENCES

VV.AA. Road Safety in Tunnels. 1995. PIARC Committee on Road Tunnels, C5

VV.AA. Fire and Smoke Control of Tunnels. 1999. PIARC Committee on Road Tunnels, C5

RABT Guidelines for equipment and operation of road tunnels (Richtlinien für die Ausstattung und den Betrieb von Strassentunneln)

Journal of laws of the Republic of Poland, nr. 63. Regulation of the Minister of Infrastructures Poz. 63

Faggioni, N., Bizzi, F., Bringiotti, M. 2016. La Ventilazione Trasversale applicata alle gallerie artificiali a traffico monodirezionale: il caso della galleria S2 di Varsavia. Gallerie 119.

Devia, F., Faggioni, N., Franzese, E. 2015. Un esempio di approccio cfd nella verifica di sistemi di ventilazione complessi a servizio di gallerie stradali. Le Strade 1506 April 2015. La Fiaccola