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An integrated approach for the analysis and modeling of road tunnel ventilation. Part I: Continuous measurement of the longitudinal airflow profile

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ABSTRACT

The knowledge of the flow field inside road tunnels under normal operation, let alone fire conditions, is only approximate and partial. The reason is that while the full three-dimensional, unsteady problem is out of reach of numerical methods, on the other hand accurate measurement of the airflow in road and railway tunnels constitutes an extremely demanding task. The present work, structured as a twofold study, takes up the challenge and proposes an original integrated experimental and numerical approach for the analysis and modeling of flow inside a road tunnel and its ventilation systems, aiming at defining a methodology for the creation of "digital twins" of the system itself, on which advanced ventilation and smoke control strategies can be tested and fine-tuned. In this first part, an innovative experimental facility for the continuous acquisition of the longitudinal velocity profile along the whole length of a road tunnel has been designed and built. The facility consists of a survey rake with five bidirectional vane anemometers, which is mounted on a small electric vehicle that can travel through the tunnel at constant speed. This paper reports the design procedure of the measurement facility, with particular focus on the conception and realization of the vehicle carrying the survey rake. Results of the first experimental campaign carried out under the 11611 meters long Mont Blanc road tunnel are presented to corroborate the validity of the approach adopted and the accuracy of the measurement chain.

1. Introduction

Airflow control is a critical issue in a large number of civil infrastructures, expecially road and railway tunnels, since it determines air quality and breathability in ordinary operating conditions, and temperature distribution and smoke movement in case of fire. Such a topic deserved great interest during the last century, and many efforts were put in the characterization (via in situ measurements, experiments on scaled models) and prediction (via numerical modelling) of the flow conditions which can take place.

The present work is framed in a long-standing research cooperation among the engineering departments of the University of Modena and Reggio Emilia, the Gruppo Europeo di Interesse Economico del Traforo del Monte Bianco (GEIE-TMB), the French-Italian consortium in charge of the maintenance and management of the Mont Blanc tunnel (TMB), and Mimesis, an engineering company specialized in fluid dynamics, concerning the study and optimization of the Mont Blanc tunnel ventilation system. Within such framework the ventilation system has been the subject of a number of studies, including accurate, multi-point in situ velocity measurements with steady anemometric facilities [1,2], simplified semi-analytical models [2] and an attempt to a full-scale CFD simulation [3].

The main aim of this joint research is to minimize the response time of the ventilation system to a fire event in the tunnel. The pursued condition consists in having all the smoke confined within a 600 meters long tunnel stretch, centered on the event, in the minimum possible time. To this aim, the availability of accurate and fast prediction methods is a crucial asset to devise, and subsequently optimize, advanced control strategies. Hence, the present study is motivated by the need to devise an integrated approach, aimed at the creation of reliable 1D numerical models of specific road tunnels with relatively complex ventilation systems, as in the case of the Mont Blanc Tunnel.

Such an approach must be based on a solid numerical algorithm for the solution of a weakly compressible flow network. The code should

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contain a toolkit, organized in modules so as to maintain maximum flexibility, in order to quickly set up a “digital twin” of a given tunnel. Since any adaptation of the numerical model to a specific tunnel would need experimental data for its calibration, the approach should necessarily include a standardized and repeatable process for gathering the field data needed for the calibration and validation of the model itself.

This first part of this twofold work is focused on the experimental technique specifically devised to collect accurate in situ measurements for the purpose of model calibration. Such data are also significantly useful to develop a deeper knowledge on this specific class of fluid dynamic systems, and also to verify the accuracy of velocity probes installed in road tunnels, which, in turn, as in the case of the Mont Blanc, generate the data which are directly fed to airflow control infrastructures.

Many of the experimental works which can be found in literature make use of scaled models, and focus on local aspects of the flow behaviour. In the work by Oka and Atkinson [4] experiments are performed in a model tunnel and use is made of Froude scaling to obtain estimates of the critical velocity required to suppress upstream movement of combustion products in case of fire. All through the last decade Salizzoni et al. [5–7] put in a solid effort in the investigation of the behaviour of the buoyant plume raising from the floor of a tunnel – which simulates a fire – and how this responds to variation of several parameters: buoyant source position and size, extraction vents position and shape, buoyant mixture velocity at the source.

A number of studies describing in situ acquisition campaigns in road tunnels can also be found in the literature. Martegani and co-workers [8] carried out tests to investigate the flow field resulting from the installation of coupled jet fans at different pitch angles. Wang et al [9] investigated jet fans performances in a very long tunnel (more than 18 km) by means of a grid of vane anemometers, placed at different locations along the tunnel.

The response to forced ventilation of vehicles and pool fires was instead studied by Carvel [10], who found that the size of a large HGV fire is greatly increased by forced longitudinal ventilation, while for small pool fires and car fires increasing the ventilation tends to reduce the size of the fire. Fire and ventilation tests performed in the Mont Blanc road tunnel in 2000 are carefully recorded and commented in [11] where the influence of the ventilation regimes used on the smoke progress is analyzed in detail.

Król and co-workers [12] carried out a thorough analysis on the effects of natural draught on the overall flow in a longitudinally ventilated tunnel – a phenomenon of great interest for the Mont Blanc tunnel as well, since the portals are at opposite sides of a huge natural divide between two environments, which can thus present very different weather. The measurement facility used consisted in two poles supporting a number of anemometers stacked vertically: by moving such poles transversely through a section, they were able to acquire flow velocity on a remarkably fine grid of measurement points. More examples of employment of frames of different shapes for the handling and positioning of multiple measurement devices can be found in the literature [13,14]. The variables of interest are generally air velocity and concentration of pollutants.

Fewer works report numerical results coupled with experimental evidence. Wu and co-workers [15,16] studied the effects of the tunnel cross sectional geometry on the critical velocity. Kashef and Bénichou [17] used experimental data as boundary conditions to validate their numerical model, and successively performed a parametric study to assess the performance of emergency ventilation strategies in a road tunnel in the event of fire. The PhD thesis by Colella [18], where a multi-scale model is adopted for the investigation of tunnel ventilation connecting three dimensional numerical simulations to a 1D model, is a very rich source of data and information, also including data from four full scale road tunnels and a small scale model.

In the framework of the present research, a first experimental rig was built, consisting of a lightweight, high-stiffness aluminum structure with negligible aerodynamic impact, conveying five bi-directional vane anemometers mounted at evenly scattered locations so as to capture the longitudinal flow in different significant points of the Mont Blanc Tunnel cross section. The instrument was successfully tested during a preliminary measurement campaign [19], and successively employed to carry out further data upon the influence of jet fans on the main tunnel flow, which have been successively employed to characterize the main integral aerodynamic parameters of the Mont Blanc Tunnel such as the average friction factor and the jet fan installation efficiency [2]. Those parameters were calculated by calibrating a simple 0D model representing the airflow in the tunnel when transverse ventilation is switched off, and the velocity field is determined only by the atmospheric pressure gradient and the activation of jet fans.

However, in normal operation, the hybrid transverse-longitudinal ventilation system of the Mont Blanc Tunnel [11] gives rise to a non-uniform longitudinal velocity profile [2], whose shape depends on the operation of a number of centrifugal fans, responsible for blowing fresh air and extracting vitiated air throughout the whole tunnel extent. The thermo-fluid dynamic behaviour of a similar system needs at least a 1D model to be properly represented. Such a model would then require a much heftier measurement database to ensure a proper calibration process. The longitudinal velocity component would need to be sampled at several locations along the tunnel, with a very fine spatial step. In fact, as it will be described in the second part of the work, the slope of the longitudinal profile depends on the air flow rate entering and exiting the system at different sections; these flow rates, in turn, are influenced by the friction characteristics of underground air supply and extraction channels, whose correct determination is of great importance to obtain an accurate modeling of the whole ventilation system.

In the case of the Mont Blanc Tunnel, and, more generally, in long mountain tunnels equipped with hybrid ventilation systems, a spatially accurate sampling of the longitudinal velocity can hardly be achieved by displacing a stationary survey rake at different locations. The variability of weather conditions at the portals could complicate the reconstruction of the correspondence between the ventilation parameters and the actual flow, since the acquisitions at different stations would be the result of different, largely unsteady boundary conditions. Moreover, such measurement campaigns are typically performed in the occasion of dedicated traffic closures, which, at best, last only a few hours, only allowing for the exploration of a limited number of positions for a single ventilation configuration [2].

For this reason, the adoption of a moving measurement facility was envisaged, allowing for a continuous pointwise acquisition of the longitudinal velocity component over the entire tunnel length. The rationale underlying the concept of the facility relies on the principle of aerodynamic reciprocity. The task of performing velocity acquisitions in a 11 km long tunnel by exploiting such a principle is anything but trivial, since it implies that the measurement device must travel along the entire tunnel length at fixed speed, following the road centerline, and must have a minimum aerodynamic impact on the airflow. On the other hand, the possible advantages deriving from the implementation of such a concept are enormous: first of all, a very fine spatial resolution of the measurements can be achieved along the axial direction, only depending on the advancement speed of the device; secondly, the influence of changes in environmental and boundary conditions on the measured airflow can be minimized; in third instance, a large variety of ventilation configurations can be tested with a relatively sustainable effort, thus allowing for a huge number of data to be collected.

Building on these premises, the T.A.L.P.A. (Tunnel Aerolab for Longitudinal Profile Acquisition) facility, presented in this work, was realized. The array of vane anemometers previously constructed and tested was mounted on the chassis of a small, electrically powered go-kart, with a negligible frontal area with respect to the tunnel section. The vehicle was equipped with a very accurate cruise control system, ensuring strict constancy of the advancement speed, and with a servo-assisted steering rack, connected to a non-proportional joystick, allowing for a precise direction control.

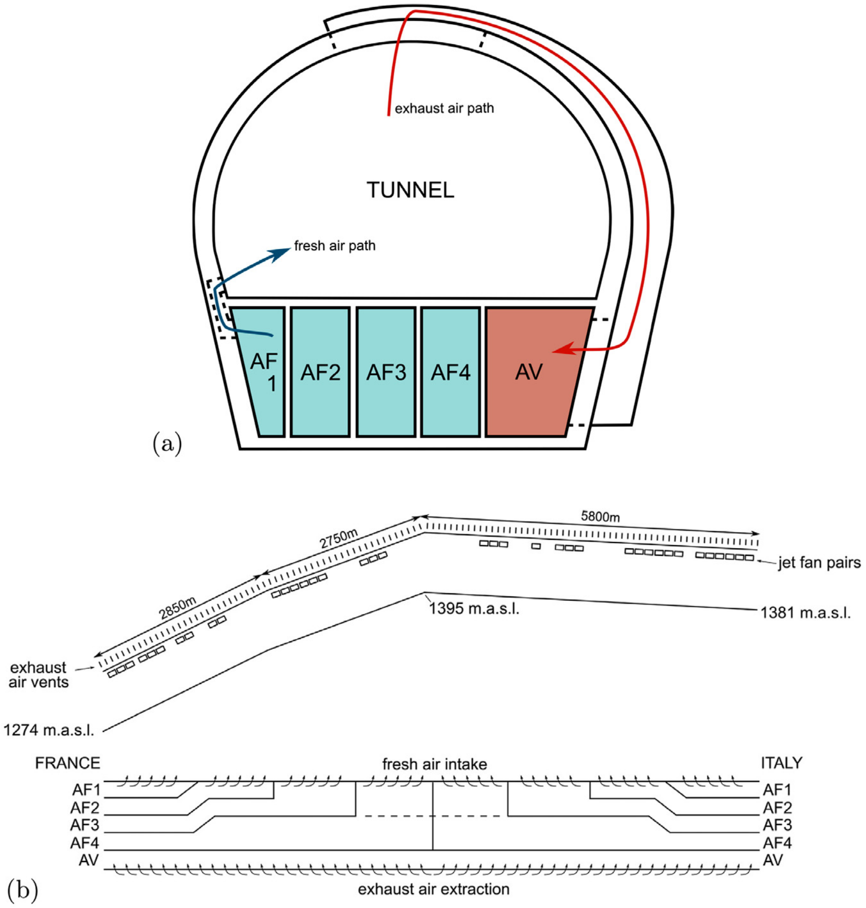

Fig. 1. Schematic representations of the Mont Blanc Tunnel ventilation system: (a) sketch of the transverse cross-section of the tunnel and underground ventilation channels with locations of fresh air and exhaust vents and indication of the corresponding flow paths; (b) sketch of the longitudinal section of the tunnel (top view) and planform of the underground ventilation channels (bottom view), from [2].

In the following, details of the design and realization of the facility are given, and results of the first measurement campaign are reported, highlighting the satisfactory accuracy and sensitivity of the measurement technique with respect to a variety of flow configurations. The results confirm the suitability of the approach for the characterization of airflow in road and railway tunnels.

2. Case study

The case of interest for the present study is the Mont Blanc Tunnel, which is a two-way, 11 km long road tunnel connecting Chamonix (France) and Courmayeur (Italy). The tunnel is endowed with of a hybrid (or semi-transverse) ventilation system, schematized in Fig. 1, whose main components are:

- a fresh air supply system composed by 8 underground channels, each one serving 1450 m of tunnel; these ducts are fed by two ventilation stations (at the Italian and French sides), each one equipped with 4 centrifugal fans (denoted by AF1-4 in Fig. 1). These fans propel fresh air into the channels; from here, air is discharged into the tunnel through small vents, placed at the bottom of the Italy-France sidewalk with a spacing of 10 m (Fig. 1(a));
- an exhaust smoke extraction system made by a couple of nonreversible centrifugal fans at each portal (denoted by AV in Fig. 1). The extraction system is completed by a series of adjustable extraction vents, located each 100 m on the tunnel ceiling and linked with one single long underground channel by suitable ducts (Fig. 1(a));
- 38 pairs of reversible axial jet fans;

Some details of the tunnel ventilation system are portrayed in Fig. 2. A list of relevant geometric parameters of the tunnel can be found in [2].

3. The T.A.L.P.A. facility

3.1. Measurement system and survey rake

A detailed description of the conception, design and realization of the measurement system, and of the construction of the survey rake, representing the first steps in the building process of the facility presented here, is reported in [2]. In particular, the choice of the arrangement of the measurement points, and their positioning across the tunnel section, the selection of the probe typology and measurement range, the signal routing chain and acquisition system, and the choice of materials and beam profiles were detailed in [2] and will not be discussed here. For the aim of the present work, it should be sufficient to recall the fundamental aspects of the measurement system and of the survey rake.

The measurement system consists in a set of five bi-directional vane anemometers (MiniAir6-Macro by Schiltknecht Messtechnik AG). The probe model was selected for its good accuracy ($\pm 0.5\%$ full scale $+1.5\%$ of reading) and the considerable extension of its measurement range (0 to 30 m/s). Vane anemometers were chosen as the best compromise between robustness, simplicity, cost, and measurement accuracy, after a careful evaluation of different anemometric techniques and types of sensors.

The five probes were dislocated in five different locations on the Mont Blanc Tunnel cross section by means of a custom made survey rake, whose geometric model is portrayed in Fig. 3. The arms of the rake carrying the probes were constructed with light aluminium alloy profiles with oval cross section. The base chassis, also made of light aluminium alloy beams, was conceived so as to be easily fitted to the frame of a small vehicle, in view of the realization of the T.A.L.P.A. facility. The structure was then completed and stiffened by steel cables, tensioning

Fig. 2. Details of the Mont Blanc Tunnel ventilation system: (left to right) interior of the ventilation central on the Italian side; underground fresh air channel; fresh air supply vents along the walkside; a pair of jet fans.

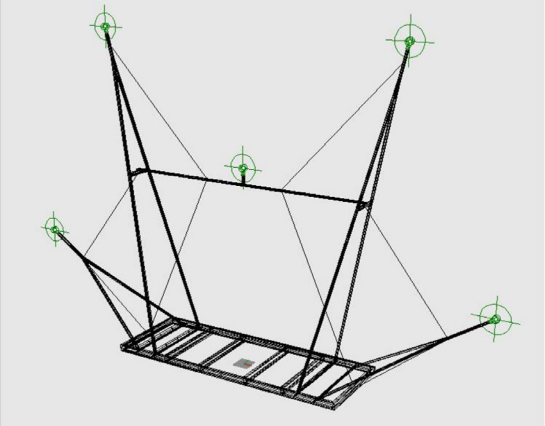

Fig. 3. 3D mathematical model of the survey rake (from [2]).

screws and rods. Throughout several tests [2,19] the rake demonstrated to fulfill all the requirements according to which it was designed, as it proved to be stiff, robust, light and transportable, and, most important, of limited aerodynamic impact. Moreover, the number and localization of the measurement points was seen to provide a satisfactory description of the longitudinal velocity profile on a standard tunnel section.

3.2. The T.A.L.P.A. vehicle

The role of the vehicle in the T.A.L.P.A. facility is to carry the survey rake along the tunnel, in order to enable a fine scanning of the longitudinal velocity profile. As previously mentioned, the structure itself carries five anemometers to measure the longitudinal air velocity component in five significant points of the tunnel cross section. The survey rake has previously been used in experimental campaigns involving fixed-position measurements, or discrete displacements of the structure at pre-defined stations inside the tunnel; instead, a continuous displacement of the survey rake would virtually allow for the measurement of longitudinal velocity at any cross-section of the tunnel.

For the principle of aerodynamic reciprocity, the indirect measurement of the longitudinal velocity is feasible when the facility runs at an exactly constant speed. In this way, the velocity values acquired when the facility is in motion can be simply offset by the vehicle speed, in order to obtain the true velocity value, therefore eliminating the need for corrections due to the acceleration terms. The main project specifications for the vehicle in the T.A.L.P.A. facility were the following:

- *Limited aerodynamic impact*: as for the survey rake, the vehicle was required to have a frontal area as small as possible, in order to minimize the perturbations induced by its advancement on the airflow to be measured.
- *Lateral stability*: the chassis of the vehicle had to be particularly stable with respect to lateral vibrations and oscillations, in order to keep the positioning of structure carrying the anemometers as firm as possible.
- *Accurate speed control*: as previously mentioned, the fundamental requirement for the feasibility of continuous measurements with the survey rake in motion is the strict constancy of the advancement speed. This should be totally insensitive to the road conditions (slopes, small obstacles as speed bumpers, different qualities of the concrete surface) and to the different aerodynamic forces due to changes in the airflow itself. In order to avoid a loss of accuracy in the velocity measurement, the absolute uncertainty in the determination of the vehicle speed must be less than the anemometers absolute error.
- *Accurate direction control*: as already stated, the survey rake has to be kept as much as possible in the same position with respect to the tunnel cross section. Such a requirement is strictly connected to the accuracy of the vehicle direction control, for which a self-centering servo-steering is necessary.
- *Fast scanning*: according to the chosen measurement principle, the spatial resolution of velocity measurements depends on the value of the vehicle advancement speed and on the sampling rate of the instruments. It is obvious that the higher the speed, the lower spatial resolution can be achieved, for a given sampling rate. On the other hand, since the tunnel airflow is extremely sensitive to changes in the boundary and environmental conditions [2,11,19] and the rate of change of the latter due to weather fluctuations is by no means controllable, it can be more advisable to let the vehicle travel as fast as possible in order to take a reasonably consistent “picture” of the longitudinal velocity profile, with practically stationary boundary conditions.

The development phase and the practical implementation of the solutions to the above requirements were carried out entirely in the facilities of University of Modena and Reggio Emilia. The main choices and features of the vehicle are now briefly described.

In order to keep the vehicle profile as low as possible, a race go-kart frame was chosen. The total height from the ground of the vehicle was then limited to 500 mm including the driver. Further advantages of a go-kart frame are the width of tyres and a very low centre of mass, which naturally provides a high lateral stability to the whole system: in fact, it has to be considered that the survey rake carried by the vehicle is up to five metres wide, and even a small lateral angular oscillation could cause a wide movement of the side arms carrying the anemometers, thus compromising measurement accuracy. To avoid any vibration, heat and gas emissions possibly affecting the measurement, a battery-

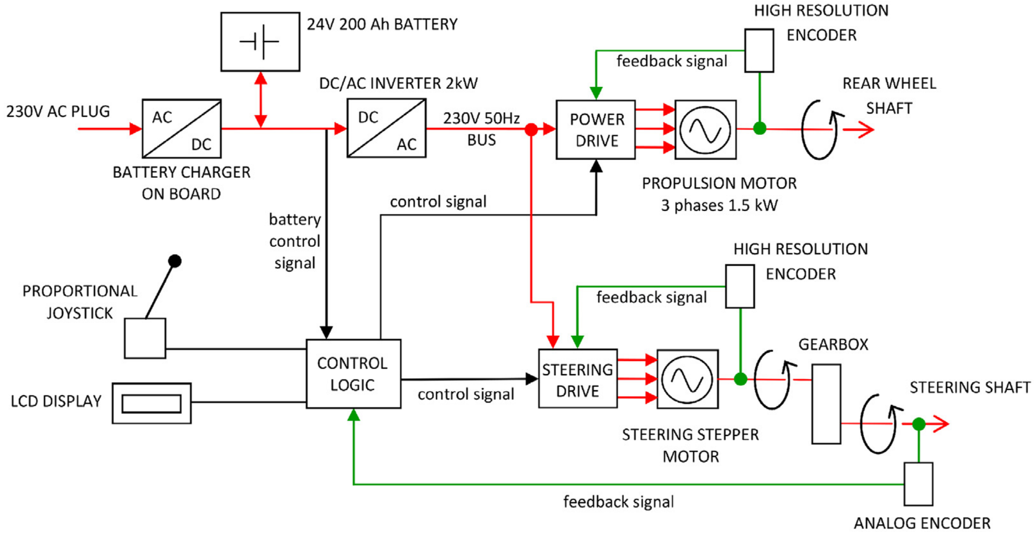

Fig. 4. Schematic of the power control and steering control loops implemented in the T.A.L.P.A. vehicle.

electric propulsion was chosen. Hence, the vehicle was equipped with two 24V 200Ah lead batteries, which ensured an average range of 60 km. In order to ensure constancy of the advancement speed, a closed-loop system was implemented (Fig. 4). The closed-loop was based on a feedback speed sensor, which could sense either the vehicle advancement speed (optical odometer) or the wheel rotational velocity (with an encoder on the wheel shaft), or, instead, the rotational velocity of the electric motor (with an encoder on the motor shaft). The motor speed was chosen as the feedback parameter because it presents the fastest transient response and, also, the easiest tuning. The transmission chain (belt, shafts, tires) can be viewed as a rigid system and the inertia of the vehicle is very low (total system mass is less than 200 kg), thus the motor speed and vehicle-speed can be assumed as proportional. Following the above considerations, the propulsion of the vehicle was realized by means of an electric servo motor with a high resolution encoder in a closed loop PID fashion. The speed error and the transient response was tested and was found to be low enough to avoid any loss of accuracy in the anemometric measurements. The problem of keeping the vehicle travelling straight in the middle of the road during testing was solved by means of an electric servo-steering powered with a precision stepper-motor in a double closed loop control (Fig. 4). The input of the steering system is the position of a joystick handled by the driver. In this way, once the driver finds the road centerline, the vehicle keeps the same direction and the driver must only make minor corrections to compensate the drift of the road or when there is a curve to follow.

As for the determination of a reasonable advancement speed of the vehicle, the best compromise between speed, motor power consumption, battery size, and, last but not least, driver safety was found at 5 m/s. At this velocity the scanning of a long tunnel like the Mont Blanc Tunnel takes approximately 40 minutes, a short time compared to the rate of climate variations at the portals and the overall inertia of the mass of air contained inside the tunnel. Another important aspect is also the effect of turbulence on the measurement probes. Assuming an average air velocity of the order of 5 m/s in the tunnel, literature correlations [20] yield a value of turbulent intensity of ≈ 2.5%, corresponding to fluctuations of the order of ≈ 0.13 m/s, i.e. comparable with the accuracy of the present probes. Moreover, given the relatively long response time of vane anemometers [21], it is reasonable to assume that the effect of turbulence around the probes is smoothed out during the measurement process and is therefore negligible.

Since the sampling rate of the probes was kept at 1Hz with an advancement speed of 5 m/s, the values of the longitudinal velocity in a cross section of the tunnel are sampled every 5 meters. The system was then finalised to keep a constant speed of 5 m/s in most of the real measurement conditions, with slopes not exceeding 12%, and air velocities below 30 m/s. The vehicle in its final layout is shown in Fig. 5(a).

4. Results and discussion

The first measurement campaign performed with the T.A.L.P.A. experimental facility took place at the Mont Blanc tunnel the night between January 21st and 22nd, 2012 (Fig. 5(b)). Throughout a time span of 8 hours, five runs along the tunnel were completed, three times from the Italian portal to the French portal and twice backwards.

Detailed information on the five tests is reported in Table 1. The facility was assembled in place during preliminary operations, by rigidly mounting the pre-built rake on the vehicle chassis. At the start of each test, the T.A.L.P.A. was aligned with the road centerline approximately 20 m outside the tunnel portal. Then, the recording of anemometric data was switched on, the motor was powered up and the cruise control system was activated before entrance in the tunnel. The driver took care of ticking the exact time instances of tunnel entrance and exit by means of a marker push-button connected to the data acquisition system, with a resolution of 1s.

The vehicle was driven by two different drivers during the tests. This choice did not affect the overall accuracy of the advancement speed control system: as reported in Table 1, the maximum difference in test duration times (approx. 39 minutes) was only of 3 s, leading to differences in the advancement speed lower than 0.01 m/s, i.e. considerably less than the average accuracy of the anemometric probes.

The five ventilation configurations tested were chosen so as to collect meaningful data for calibration of a simplified fluid dynamic model and to build a sufficient basis for the characterization of a number of important parameters of the ventilation system, such as the flow rate distribution and pressure loss coefficients of fresh air inlet and extraction vents, and the extent of local air jets due to the operation of axial fans. During test 1, the flow was induced by the transverse ventilation system, adding to the significant influence of the pressure difference between the tunnel ends; the rotational velocity of fans providing transverse fresh air inlet in the tunnel was kept at a constant value $n_{AF} \approx 650$ rpm, with all jet fans and air extraction deactivated. Test 2 was performed with the same configuration, but with air extraction activated along a 600 meters long tunnel stretch, located in the vicinity of the French portal. Test 3 and 4 were conducted in a similar fashion, but keeping the fresh air flow rate $Q_{in,ch}$ roughly constant, between 43 and 44 m^3/s, with air extraction once again activated only in the second of

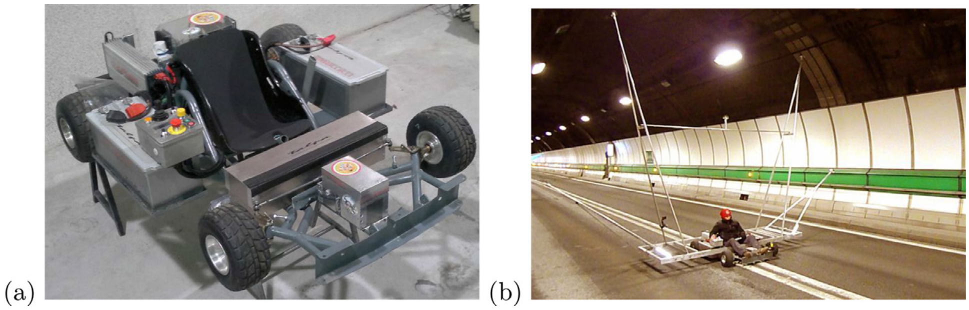

Fig. 5. (a) The vehicle in its final layout (b) The T.A.L.P.A. facility traveling through the Mont Blanc tunnel during the measurement campaign. tunnel during the measurement campaign.

Table 1
Details of the five experimental tests including average pressure and temperature values at the portals, net pressure gradient and natural draught velocity, total flow rates through the ventilation channels (inlet and outlet), settings for fresh air supply, reference metric points for the opening of extraction vents, number of active jet fans and their direction.

Test no.	1	2	3	4	5
Start time [hh:mm]	23:02	00:26	01:38	02:40	04:09
Test duration [s]	2308±1	2311±1	2308±1	2311±1	2308±1
Vehicle speed [m/s]	5.031±0.002	5.031±0.002	5.024±0.002	5.024±0.002	5.031±0.002
weather data					
p_F [Pa]	87578±9	87581±10	87542±8	87512±7	87483±13
p_I [Pa]	86074±8	86045±18	85999±5	86004±10	86005±7
T_F [°ìC]	0.1±0.1	0.1±0.1	0.1±0.1	0.1±0.1	0.7±0.1
T_I [°C]	4.4±0.1	5.4±0.1	5.4±0.1	5.2±0.1	4.8±0.1
ventilation data					
Δp_eff	407±12	403±15	447±8	375±15	373±15
U_nat [m/s]	4.56±0.07	4.50±0.08	4.77±0.04	4.35±0.09	4.35±0.09
fresh air supply	on	on	on	on	off
setting	$n_\mathrm{AF} \approx 650$ rpm		$Q_\mathrm{in,ch} \approx 43 \div 44$ m^3/s		-
$Q_\mathrm{in,tot}$ [m^3/s]	371.2±3.9	374.7±5.7	344.8±5.1	351.6±6.7	-
air extraction	off	on	off	on	on
extraction stretch [m]	-	835÷1435	-	835÷1435	9035÷9635
$Q_\mathrm{out,tot}$ [m^3/s]	-	261.2±10.1	-	287.0±34.7	285.4±1.1
active jet fans	off	off	off	off	$4_{\mathrm{F}\rightarrow\mathrm{I}} + 4_{\mathrm{I}\rightarrow\mathrm{F}}$

the two tests, i.e. test 4, along the same tunnel stretch considered for test 2. A radically different configuration was instead tested in the last run: the fresh air supply fans were completely switched off, four couples of jet fans were operated (two in each direction), and air extraction was activated along a segment 600 m long, 2 km far from the Italian portal.

As reported in Table 1, the barometric pressure recorded at the two portals remained fairly constant during each test, with deviations of less than 15 Pa for the temperature difference. On the other hand, the weather conditions during the measurement night were such that a significant natural draught ensued in the tunnel. As it will be shown, such a flow component crucially influenced the resulting velocity profiles established for each of the five tested configurations. Thus, an a posteriori estimate was carried out to evaluate the average velocity that would establish in the tunnel during each test, due to the sole effective pressure gradient Δp_eff. The latter can be defined as the pressure difference between the two tunnel ends minus the overall hydrostatic load [2]:.

$$\Delta p_\mathrm{eff} = p_\mathrm{F} - p_\mathrm{I} - g \int_0^{L_t} \rho \sin\theta \, dx \tag{1}$$

where p_F, p_I are the absolute pressure values measured by the weather stations at the portals, $g = 9.798$ m/s^2 is the gravitational acceleration, θ is the slope angle of the tunnel, L_t the tunnel length and x the longitudinal coordinate (also called Metric Point or PM throughout the present discussion). The calculated values of Δp_eff are reported in Table 1 and range between 373 Pa (test n.5) and 447 Pa (test n.3). Such values amount approximately to 50-60% of the limit value (750 Pa) beyond which traffic is stopped at the Mont Blanc Tunnel and, thus, confirm the presence of a strong natural flow component. The resulting natural velocity was calculated by using the 0D model for longitudinal ventilation derived in [2], by assuming steady-state conditions:

$$u_{nat} = \sqrt{\frac{2\Delta p_\mathrm{eff}}{\rho_\mathrm{ave}\left[\frac{\rho_\mathrm{ave}}{\rho_\mathrm{in}}(k_\mathrm{in}+1) + \frac{f\,L_t}{D_h}\right]}} \tag{2}$$

where: k_in and f are the concentrated loss coefficient at the inlet and the tunnel friction factor, respectively; D_h is the hydraulic diameter of the tunnel; ρ_ave and ρ_in are the density values calculated at the average temperature in the tunnel and at the tunnel end where the natural flow enters the tunnel (in the present case, the French portal), respectively. Values of friction coefficients f and k_in have been taken from the results of a previous study [2]. Concerning the calculation of density, the ideal gas law with a fixed reference pressure was used (see again [2]). While a broad estimate of the temperature profile inside the tunnel could be a reasonable choice for the estimation of the average density [22] and, also, of the integral term of (1), a more accurate calculation was made possible by the continuous acquisition of temperature by means of a thermocouple mounted aboard the T.A.L.P.A. vehicle. The acquired temperature profiles during all the five tests are displayed in Fig. 6.

The velocity values associated with natural draught are reported in Table 1, and plotted along with the measured velocity profiles in Figures 7 to 11. Calculated values range from a minimum of 4.35 m/s (test n. 4 and 5) to a maximum of 4.77 m/s (test n. 3). It is worth to note that the temperature distributions, which have a crucial impact on the entity of the hydrostatic load, are significantly influenced by the ventilation configurations. For instance, Fig. 6 clearly shows that in test 1 and 3, where, as shown in Figs. 7 and 9, air exits from both portals, temperature at both tunnel ends is higher than the outside temperature. This is due to the fact that the air blown by fresh air fans is preheated while passing through the AF channels (see Fig. 1) before entering the tunnel.

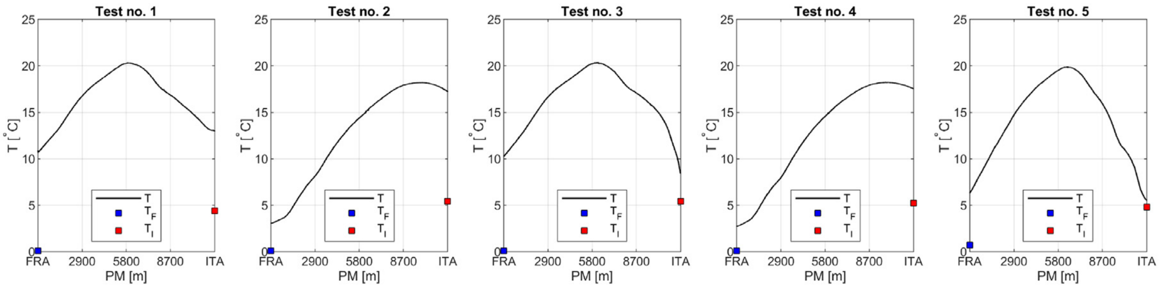

Fig. 6. Temperature profile as a function of the longitudinal tunnel coordinate (Metric Point, PM) recorded during the five T.A.L.P.A. runs.

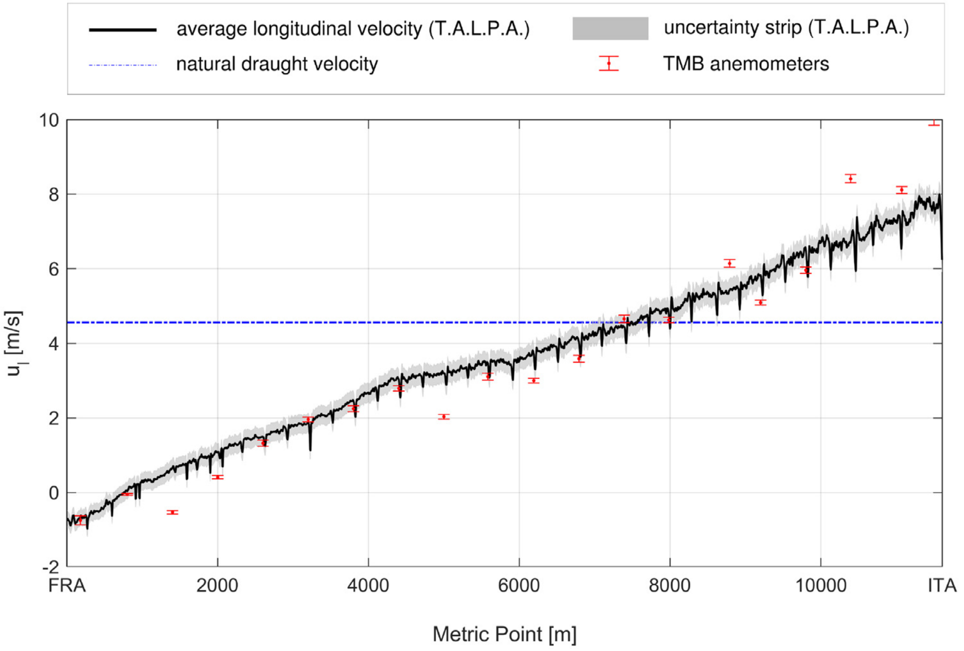

Fig. 7. Velocity profile as a function of the longitudinal tunnel coordinate (Metric Point, PM) reconstructed for test n. 1. An uncertainty strip for present measurement is added to the graph, as well as the estimated natural draught and the velocity values measured by the 20 ultrasonic anemometers of the TMB S.C.A.D.A. system.

On the other hand, during tests 2 and 4, air enters from the French portal and exits from the Italian portal (see Figs. 8 and 10): hence, air temperature at the inlet section is closer to the value recorded at the portal, and increases almost monotonically along the longitudinal coordinate, with only a slight decrease due to mixing with cooler fresh air near the Italian exit. Finally, the absence of fresh air supply in Test 5, adding up to the air extraction, causes the air to enter the tunnel at both portals (Fig. 11); this results in a sharper temperature distribution, the values at tunnel ends being closer to those recorded by the TMB weather stations.

Despite the evident connection between the available temperature data and the ventilation setup, which does not reflect, in general, the temperature profile one would obtain with the sole contribution of natural draught, such data were equally used to estimate natural flow velocity for each test. Nevertheless, these estimates can be considered as equally representative of the natural draught effect and be useful to interpret the velocity distributions resulting from the different ventilation configurations.

As already mentioned, Figs. 7 to 11 report the acquired velocity data for all the five tests, after appropriate post processing. The collected time series were suitably transformed into spatial distributions by simply multiplying the time coordinate by the vehicle advancement speed. Signals of the five anemometers were then averaged, and absolute air velocity values were then obtained by subtracting the advancement speed itself. Consistently, the uncertainty strips reported in the graphs refer to the measured velocity values, and not to the absolute air velocity, which is an indirect product of the measurement process. It is worthy to point out that the device seems to be extremely responsive to local conditions, as the profiles show the appearance of regularly spaced troughs, corresponding to local enlargements of the tunnel section in presence of safety garages.

All the graphs in Fig. 7 to 11 reveal the presence of a regular flow, coherent with the specific settings of the ventilation systems and the environmental conditions outlined above. In tests 1 and 3 (Fig. 7 and 9), the flow entering through the air vents mixes with the main tunnel flow and then exits at both tunnel openings, approximately 10% out of the French side and 90% out of the Italian exit. The velocity profiles are coherent with the specific ventilation settings adopted: in test 1 (Fig. 7), constant rotational velocity of the fresh air fans induces different flow rates in different tunnel segments, hence different slopes in the velocity profile are in order. In test 3 (Fig. 9), rough constancy of the fresh air flow rate determines a more homogeneous slope of the whole velocity profile. In both tests, due to the strong pressure gradient between the two portals, the “zero velocity point” is located very close to the French exit. On the contrary, as a consequence of the activation of air extraction devices, in tests 2 and 4 (Figs. 8 and 10) the longitudinal flow is always directed towards the Italian exit and progressively accelerating, except where extraction vents are opened. As for test 5 (Fig. 11), the absence of transverse ventilation causes the velocity profile to be roughly constant along the whole tunnel length, with a small decrease in the direction France-Italy, due to the fact that, when the vitiated air extraction fans are switched on, a fraction of the flow rate leaks through the closed air vents. As it will be shown in part II of the present twofold work, the detection of such leakages and their correct representation in the frame of a 1D flow model is of extreme importance for the accuracy of the

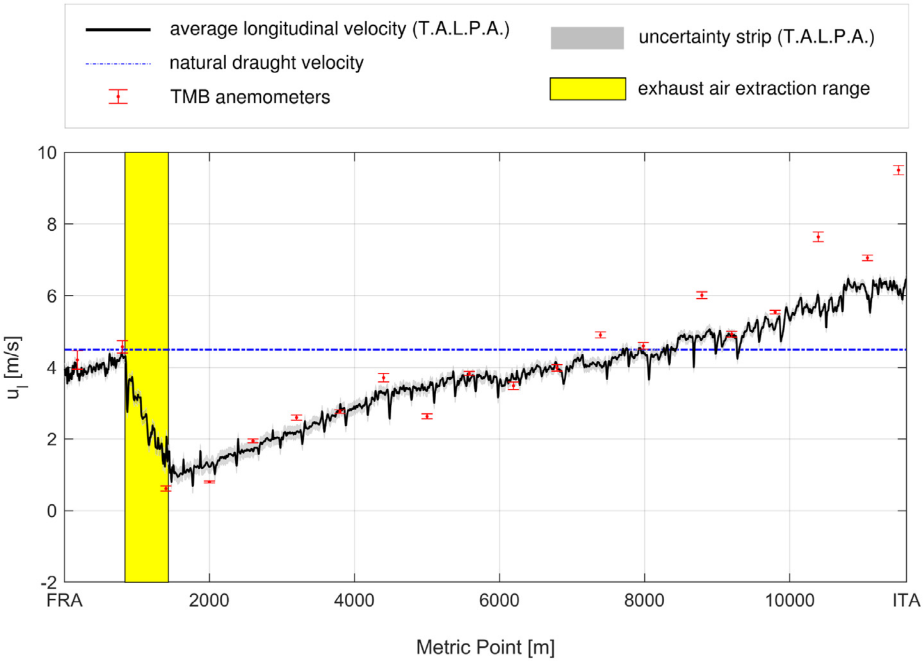

Fig. 8. Velocity profile as a function of the longitudinal tunnel coordinate (Metric Point, PM) reconstructed for test n. 2 (see also the caption to Fig. 7). The tunnel stretch where air extraction takes place is highlighted in the plot.

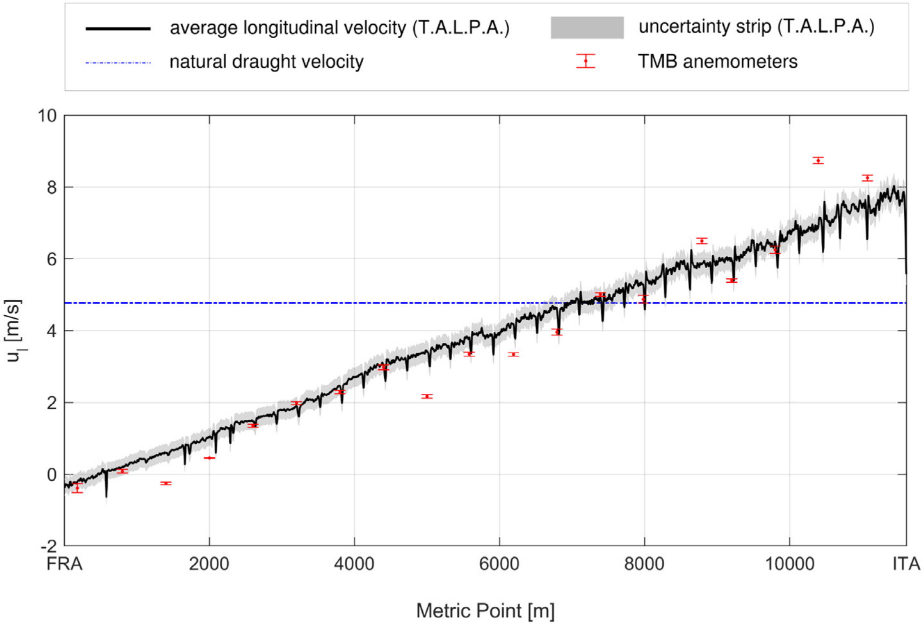

Fig. 9. Velocity profile as a function of the longitudinal tunnel coordinate (Metric Point, PM) reconstructed for test n. 3 (see also the caption to Fig. 7).

numerical tool itself. The regularity of the velocity profile is interrupted in the air extraction area only, where, as already mentioned, velocity changes its sign, and air is drafted in from the Italian portal. Hence, it appears evident that the activation of jet fans has a significant influence only on the overall flow and not on the local average velocity values, as also observed in [2].

Figs. 7 to 11 also bring forth a comparison between the present measurements and longitudinal velocity values acquired simultaneously by the 20 ultrasonic anemometers of the TMB S.C.A.D.A. (Supervisory Control And Data Acquisition) system, installed on the tunnel ceiling [2]. The two data sets present a satisfactory general agreement, both in terms of global trend and of local values. However, some of the TMB data show significant deviations with respect to the overall tendency depicted by present tests. In some cases, such deviations are systematic and do not depend on the specific ventilation configuration. These local discrepancies have already been discussed in [2], where they were ascribed either to inaccuracy of the probes or to a peculiar installation position (such as in the wake of protruding objects). In some cases, it is the complexity of the flow on the specific sections which could cause a bias in the measurements of the TMB anemometers: this is the case of test 5, where active jet fans determine a local increase in the longitudinal velocity near the tunnel ceiling, which is captured by the ultrasonic anemometers (Fig. 11), but it is not representative of the actual mean flow.

5. Concluding remarks

An innovative experimental facility for continuous, multi-point longitudinal velocity measurements in road and railway tunnels has been designed and built, and finally tested. Overall the methodology can be judged reliable and accurate, and demonstrated capable of performing

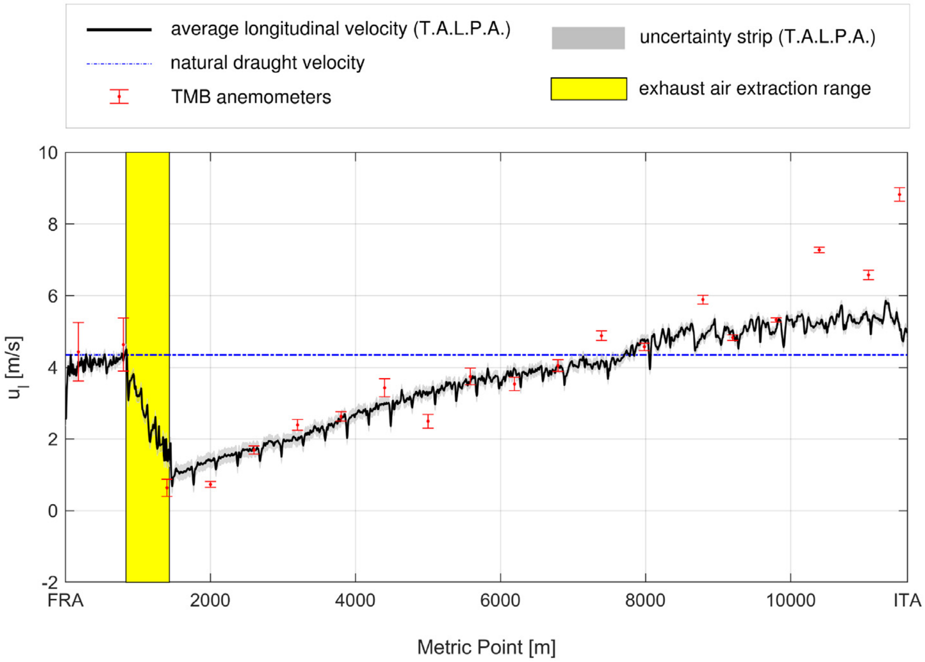

Fig. 10. Velocity profile as a function of the longitudinal tunnel coordinate (Metric Point, PM) reconstructed for test n. 4 (see also the caption to Figures 7 and 8).

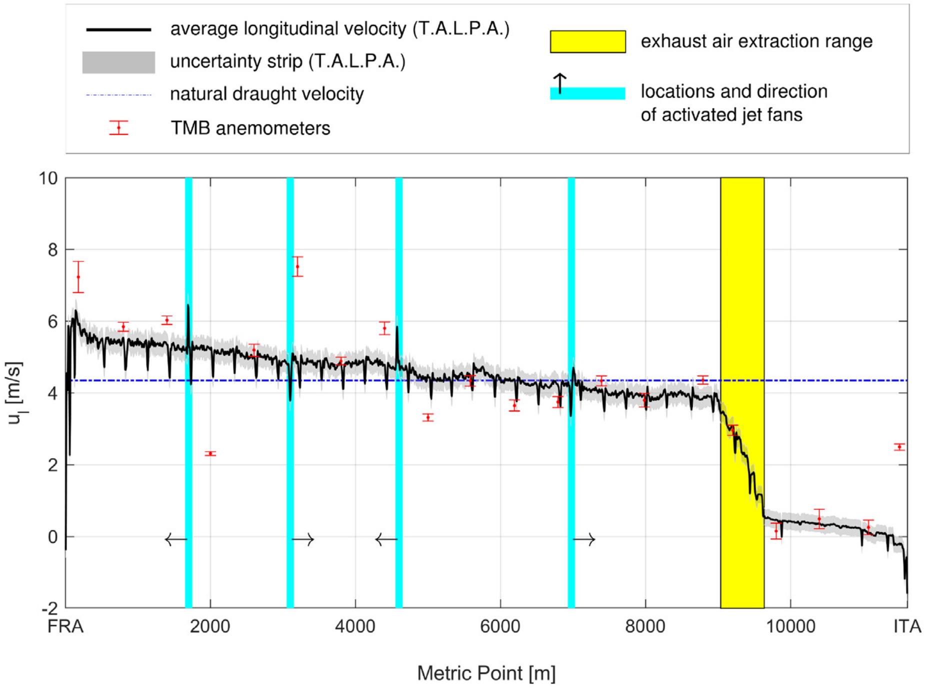

Fig. 11. Velocity profile as a function of the longitudinal tunnel coordinate (Metric Point, PM) reconstructed for test n. 5 (see also the caption to to Figures 7 and 8). Locations and direction of activated jet fans are also added to the plot.

continuous axial flow measurements under a wide range of ventilation conditions.

The validity of the methodology is confirmed by the results of the first measurement campaign, where an unprecedented quantity of anemometric data has been collected in real ventilation scenarios of the Mont Blanc Tunnel, one of the longest road tunnels in Europe.

In the second part of the present work, the collected data will be used as the basis for the calibration of a 1D numerical model of the Mont Blanc Tunnel, thus completing the determination of a global, integrated experimental and numerical approach for the analysis and modeling of road tunnel ventilation systems, potentially applicable to all large road and railway infrastructures where airflow control is of fundamental concern.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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