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# Development and calibration of a 1D thermo-fluid dynamic model of ventilation in tunnels

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## Abstract.

In complex, large civil infrastructures where ventilation has a crucial role for the safety of users in both normal operation and hazardous scenarios, the correct prediction of flow and heat transfer parameters is of fundamental importance. While full 3D simulation is applicable only to a limited extent, and the resort to 1D modeling is a common practice in both design and evaluation phases, the limitation of such models lies in the choice of transfer parameters, such as friction loss coefficients and heat transfer coefficients. In this work, an original approach based on the Finite Volume integration of the 1D flow and energy equations is presented. Such equations are to be solved on a network of ducts, representing the ventilation system in the 11.6 km long Mont Blanc Tunnel with a spatial resolution of 10 m. A preliminary calibration of a set of friction loss coefficients against a rich experimental dataset collected throughout a dedicated set of in situ tests is of particular concern here, as it is carried out by means of genetic optimization algorithms. Predictions of the flow field are in remarkable agreement with the experimental data, with an overall RMS error of  $\pm 0.42$  m/s. Further refinements and possible parameter choices are also discussed.

## 1. Introduction

Airflow control is a critical issue in a large number of civil infrastructures, such as 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. To this aim, the availability of accurate, fast and reliable prediction methods is a crucial asset to devise, and subsequently optimize, advanced control strategies.

A considerable amount of studies dealing with tunnel ventilation and fire emergency management consist of experimental campaigns performed on scaled models, primarily aimed at the investigation of the effect of different airflow control parameters on the confinement velocity [1, 2, 3]. Concerning numerical modelling, several approaches are documented in the literature, ranging from 1D models based on Hardy-Cross-like methods [4, 5, 6], to 3D Computational Fluid Dynamics (CFD) [7, 8]. Analytical 0D models have been employed for some specific applications



[9, 10]. Multiscale models, combining the advantages of both 1D and 3D approaches, have also been successfully applied, as documented by the work of Colella et al. [11, 12, 13].

Only in a very limited number of cases, one dimensional models have been finely tuned based on the results of an experimental campaign. As an example, Jang and Chen, used a 1D model in an optimization procedure aimed at the determination of the aerodynamic coefficients of highway tunnels [14]. The optimization, performed on the basis of detailed experimental measurements, is able to provide the pressure rise coefficients of the jet fans, the wall friction coefficient and the averaged drag coefficients of small-sized and large-size vehicles.

The present work is framed in a long-standing research cooperation among the engineering departments of the University of Modena and Reggio Emilia, GEIE-TMB and Mimesis, an engineering company specialized in fluid dynamics, concerning the study and optimization of the Mont Blanc tunnel ventilation system. The main aim of the research work 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 700 m tunnel stretch, centered on the event, in the minimum possible time. To this aim, the ventilation system has been the subject of a number of studies, including accurate, multi-point in situ velocity measurements, with both steady [15] and moving [16] anemometric facilities, simplified semi-analytical models [10] and an attempt to a full-scale CFD simulation [17].

One of the ultimate objectives of the aforementioned research entails the development of a specific computational tool, tailor-made on the case study and capable of predicting the air flows within the tunnel and ventilation ducts, in conjunction with the representation of the control algorithms that govern the activation and deactivation of the fans, in the pursuit of the required flow conditions. The development of a similar tool from scratch, as opposed to the resort to standard commercial 1D network flow solvers or well-known general-purpose scientific computation packages, presents several advantages, which include the high degree of customization, ease of portability and deployment and code reusability, for example in a multiscale environment.

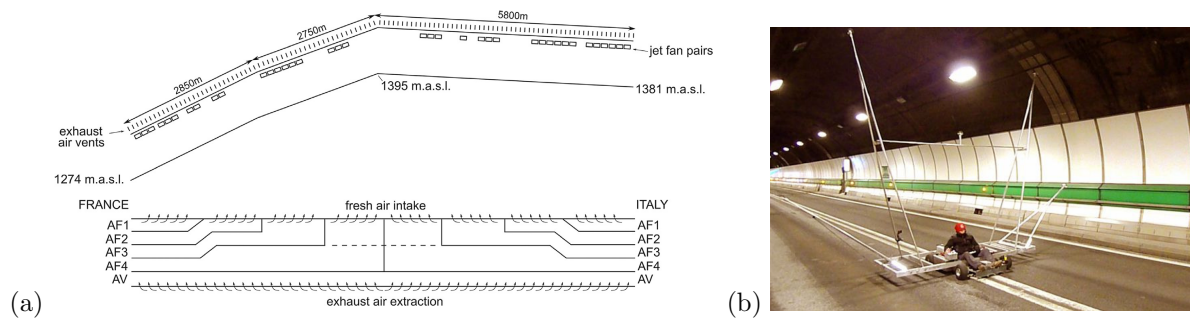
For this reason, a 1D numerical model has been developed and implemented in Python language, under an object oriented logic which makes the code flexible and adaptable to a number of different problems. Within the model, all the specific features of the tunnel ventilation system are represented by one or more lumped parameters (e.g. concentrated loss coefficients, wall heat transfer, fans). Such an approach gives a satisfactory approximation of the behavior of the physical system, provided that the parameters are finely tuned based on reliable data of the physical system.

Throughout this work, the development of the numerical model, from governing equations and assumptions to the actual iterative procedure is broadly outlined. Then, a preliminary calibration procedure of the such a model is brought forth and described. The experimental dataset collected by means of a continuous airflow acquisition facility [16] is used as reference for the accurate determination of concentrated and distributed pressure loss parameters, which is performed by means of genetic optimization algorithms. In spite of its obvious lesser degree of accuracy with respect to full scale models, the present method stands as a convenient and rapid tool to investigate different event scenarios in the tunnel. Moreover, the presented approach could be very easily replicated to a large variety of analogous situations.

## 2. Case study

The Mont Blanc Tunnel is 11,611 m long and acts as a connection between Chamonix (France) and Courmayeur (Italy) for road vehicles. The French portal is located approximately at an altitude of 1274 m while the Italian portal is set at 1381 m above sea level (Fig. 1). The two-way road is about 8 m wide and has a maximum height of about 6 m, for a cross section of 45.2 m<sup>2</sup>.

The domain of interest of the present study is represented by the road tunnel itself and its



**Figure 1.** (a) Schematic of the Mont Blanc Tunnel ventilation system: longitudinal section of the tunnel (top view) and planform of the underground ventilation channels (bottom view). Vertical and transverse dimensions are intentionally left out of scale; (b) The continuous acquisition facility traveling through the Mont Blanc tunnel during the measurement campaign.

ventilation system. With reference to Fig. 1, the main components of the ventilation system are:

- a fresh air intake 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 discharge fresh air into the channels; from here, air is discharged into the tunnel through small vents, placed at the bottom of the ItalyFrance sidewalk with a spacing of 10 m;
- 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 long underground channel;
- 38 pairs of reversible axial jet fans;

A list of relevant geometric parameters of the tunnel can be found in [10].

### 3. Experimental campaign

The experimental data required for the calibration of the model has been gathered through an measurement campaign carried out by Levoni et al. [16] by means of an innovative measurement facility, capable of performing a longitudinal scan of the air velocity of the tunnel. Such facility is made up with a survey rake with five bidirectional vane anemometers, which is mounted on a small electric kart that can travel through the tunnel at constant speed and has limited aerodynamic impact 1(b).

The measurement campaign tested five different ventilation configurations:

- During Test 1, the flow was forced by the transverse ventilation system, under the influence of the pressure difference between the tunnel ends; the rotational velocity of fans providing transverse fresh air inlet in the tunnel was kept constant at 650 rpm, with all jet fans and air extraction deactivated.
- Test 2 was performed with the same configuration, but with air extraction activated along 600 m, in the vicinity from the French portal.
- Tests 3 and 4 were conducted in a similar fashion as Tests 1 and 2, but keeping the fresh air supply roughly constant, with air extraction activated in Test 4 only.
- A different configuration was tested in Test 5: the transverse ventilation was deactivated, four couples of jet fans were operated (two in each direction), and air extraction was activated along a segment 600 m long, 2000 m far from the Italian portal.

The barometric pressure recorded at the two portals remained fairly constant during each test, with deviations of the pressure difference of less than 30 Pa.

#### 4. Numerical method

##### 4.1. Governing equations

The problem is stated under the hypotheses of steady-state, 1D flow. In this framework, the continuity, Navier-Stokes and energy equations reduce to the following:

$$\frac{\partial(\rho u)}{\partial x} = 0 \quad (1)$$

$$\frac{\partial P}{\partial x} = -\sigma_{loss} + \sigma_{fan} \quad (2)$$

$$\frac{\partial T}{\partial x} = \sigma_E \quad (3)$$

where  $P$  is the total pressure, defined as:

$$P = \frac{\rho u^2}{2} + p + \rho g(z - z_0) \quad (4)$$

and air is considered as an incompressible ideal gas, hence:

$$\rho = \frac{p_{ref}}{RT} \quad (5)$$

In Eq. (5),  $p_{ref}$  is a reference pressure, suitably chosen so as to represent the average absolute pressure in the system.

The terms  $\sigma_{loss}$ ,  $\sigma_{fan}$  and  $\sigma_E$  represent source/sink terms to account for friction losses, presence of fans, and wall heat transfer, respectively.

##### 4.2. Topological representation

As previously mentioned, the whole system (tunnel and ventilation channels) is conveniently represented by a directional graph. All the state variables (temperature, pressure, density, specific heat) are defined on nodes, while flow properties (velocity or flow rates) and source/sink terms are defined on branches. The graph topology is entirely represented by the incidence matrix  $\mathbf{A}$  [18].

Such a topological framework represents an ideal support for Finite Volume discretization: the definition of two different sets of connected objects allows to stagger the domains of integration of  $u$  (branches), and  $P, \rho, T$  (nodes).

Test	1	2	3	4	5
$p_{FRA}$ [Pa]	87578±9	87581±10	87542±8	87512±7	87483±13
$p_{ITA}$ [Pa]	86074±8	86045±18	85999±5	86004±10	86005±7
$T_{FRA}$ [°C]	0.1± 0.5	0.1± 0.5	0.1± 0.5	0.1± 0.5	0.7± 0.5
$T_{ITA}$ [°C]	4.3± 0.5	5.4± 0.5	5.4± 0.5	5.2± 0.5	4.8± 0.5

**Table 1.** Average pressure and temperature values at the portals during the experimental tests.

#### 4.3. Discrete equations

The discrete form of Eq. (1), (2) and (3) on the aforementioned system reads:

$$\sum_j a_{ij} A_j \rho_j u_j = 0 \quad (6)$$

$$\sum_i a_{ij} P_i + \Delta P_{fan,j} - \Delta P_{loss,j} = 0 \quad (7)$$

$$\sum_j a_{ij} A_j u_j T_j = \sigma_{E,i} \quad (8)$$

As  $a_{ij}$  refers to an element of the incidence matrix, index  $i$  corresponds to a node and  $j$  to a branch. Temperature and momentum source terms, along with friction losses, are defined as follows:

$$\sigma_{loss,j} = \left( \frac{f_j L_j}{D_{h,j}} + \beta_j \right) \frac{\rho_j u_j |u_j|}{2} \quad (9)$$

$$\sigma_{fan,j} = c_0 + c_1 u_j + c_2 u_j^2 \quad (10)$$

$$\sigma_{E,i} = \frac{(T_i - T_\infty)}{\rho_i c_i} \sum_j a_{ij} \frac{U_j S_j}{2} + \frac{\dot{Q}_{f,j}}{\rho_i c} \quad (11)$$

The variables introduced by equations (9), (10), (11), which are defined on branches and depend on local velocity, have been linearized to the form of  $\sigma = mu + k$ . Velocity at the previous iteration  $k$  has been employed to incorporate nonlinear terms in the coefficient  $m$  for iteration  $k + 1$ , e.g.:

$$m_{j,loss,k+1} = \rho_j \left( \frac{f_j L_j}{D_{h,j}} + \beta_j \right) \frac{|u_{j,k}|}{2} \quad (12)$$

Concerning wall heat transfer source terms  $\sigma_E$ , suitable transfer functions are used to map the coefficients  $m_{j,E}$  and  $k_{j,E}$ , defined on branches, onto the matrix and right-hand-side of the energy equation, which is solved on the nodes.

Eqs. (6), (7), (8) are solved by means of an adapted version of the well-known *SIMPLE* algorithm [19], see [12] for details. Pressure and velocity are divided into a guessed field ( $u^*$  and  $P^*$ ) and a variable correction field ( $u'$  and  $P'$ ).

$$u = u^* + u' \quad (13)$$

$$P = P^* + P' \quad (14)$$

The core of the process is then the solution of a properly defined equation, which should allow to calculate the corrections of  $P$  and  $u$  so as to comply with both mass and momentum conservation. After each predictor-corrector step, the energy equation is solved with the updated fields, and density is finally updated accordingly. The iterative procedure stops when the infinity norm of the pressure correction field  $\|P'\|_\infty$  lies within a specified tolerance.

Variable	DOE range	Optimization range
$\epsilon_{AF}$	[0.005, 0.05]	[0.001, 0.1]
$\epsilon_{AV}$	[0.005, 0.05]	[0.001, 0.1]
$\beta_{trap,open}$	[5, 50]	[0.5, 500]
$\beta_{trap,shut}$	[ $10^3$ , $10^4$ ]	[ $10^2$ , $10^6$ ]
$\beta_{vent}$	[1, 10]	[0.1, 100]

**Table 2.** Parameters range for DOE and optimization processes.

#### 4.4. Model calibration

The 1D network built up to represent the Mont Blanc Tunnel ventilation system is made up of 2465 nodes and 3730 branches, with a spatial resolution of 10 m in the tunnel and AF channels, and a resolution of 100m in the AV channels (see Fig. 1a). The geometric features (length, section area and perimeter) of the system are known for every branch in the network; so are the fan working curves. This does not apply to fluid dynamic characteristics such as friction loss coefficients: the measurement of these parameters is not a feasible option. In order to obtain a satisfactory approximation of the behavior of the physical system, channel friction losses must be finely tuned based on reliable data of the physical system. Here, the calibration procedure of the 1D model is brought forth and described.

The choice of calibration parameters is a delicate issue, as increasing their number also implies increasing the number of tests to be run to explore a sufficiently wide region of the parameters space. In the present work, five parameters were considered:

$\epsilon_{AV}$  equivalent roughness of the exhaust air channel walls

$\epsilon_{AF}$  equivalent roughness of the fresh air channels walls

$\beta_{trap,open}$  concentrated loss coefficient of an open exhaust air vent. As the precise geometry of the ducts connecting the channels to the tunnel is far from being regular, it is an appropriate choice to represent all the energy losses in such sections with a single concentrated loss coefficient;

$\beta_{trap,shut}$  concentrated loss coefficient of a shut exhaust air vent: as their open/closed state is determined by adjustable locking grates, a small leak has to be taken into account;

$\beta_{vent}$  concentrated loss coefficient of a fresh air vent.

As far as the friction factor of the tunnel is concerned, the value  $f = 0.0235$  previously determined by Levoni et al. [10] has been retained.

The objective function to be minimized is the overall root mean square deviation between the calculated and measured velocity values on 1115 points uniformly spread along the main tunnel, for all the five experimental cases. Being the error function far from linear, and likely to show a number of local minimum points, gradient methods ought to be excluded: moreover, possible discontinuities due to occasional missed convergence of the calculations would compromise the evaluation of gradients. Hence, the problem solution should employ a stochastic method, at least for a first phase of space exploration; to this aim, DES (derandomized evolution strategy) is a suitable choice, thanks to its versatility. Since evolutionary methods rely on the mutation operator rather than on cross-over and thus promote an explorative behaviour, these are convenient tools if a wide scan on the possible parameter combinations is a priority.

A Latin Hypercube Design of Experiments (DOE) [20] has been set up first to generate an initial population of 20 individuals, i.e. 20 sets of the input parameters to be calibrated. The number of values the variables can assume in the initial DOE is restricted and generally small, and their range could be changed for the subsequent optimization process, if needed. Table 2 shows the ranges that were chosen for the present calibration process.

After the initial population has been generated, the optimization procedure starts. At each step, the algorithm selects a number of sets made of a main parent (its attributes vector being called  $x_i$ ) and three other individuals ( $x_a, x_b, x_c$ ), and proceeds to the creation of mutant individuals  $v_i$  of the form:

$$v_i = x_i + K(x_a - x_i) + F(x_b - x_c) \quad (15)$$

Within equation (15), two perturbations are applied to the parent individual attributes: one based on the difference, in terms of each attribute, calculated between the parent and another individual of his generation, and another based on the comparison of two other individuals of the same generation. The magnitude of such perturbations is controlled by two coefficients:  $F$  – called scaling factor – and  $K$  – combination factor. Both  $K$  and  $M$  were set to 0.8. In order to create the new individual, then,  $v_i$  undergoes a cross-over with its parent  $x_i$ , with the cross-over constant  $C$  being the probability that the mutant phenotype will be chosen.  $C$  was set to 0.9.

The probability for a sample of being selected for generation is proportional to its fitness function. The chosen selection method follows a roulette wheel approach: the probability of being selected for the best individual in the population is  $P$  times larger than that for the worst.  $P$ , called roulette wheel selection probability bias, has been set to 3 for the first 800 individuals and was then increased to 3.5. This is due to the fact that it is better – at an initial stage – to privilege space exploration, while favouring the fittest individuals at an advanced stage may help reaching an optimum solution quicker. The procedure stops after a prescribed number of total individuals evaluated is reached, and the optimum solution is singled out based on the values of the objective function.

## 5. Results

The calibration process has taken 200 generations of 20 individuals each, for a total of 4000 evaluations of the error function. Each evaluation required five simulation runs. The parameter set which has shown to be the best fit is reported in Table 3. RMS deviations from experimental data, for each of the five cases, are also reported.

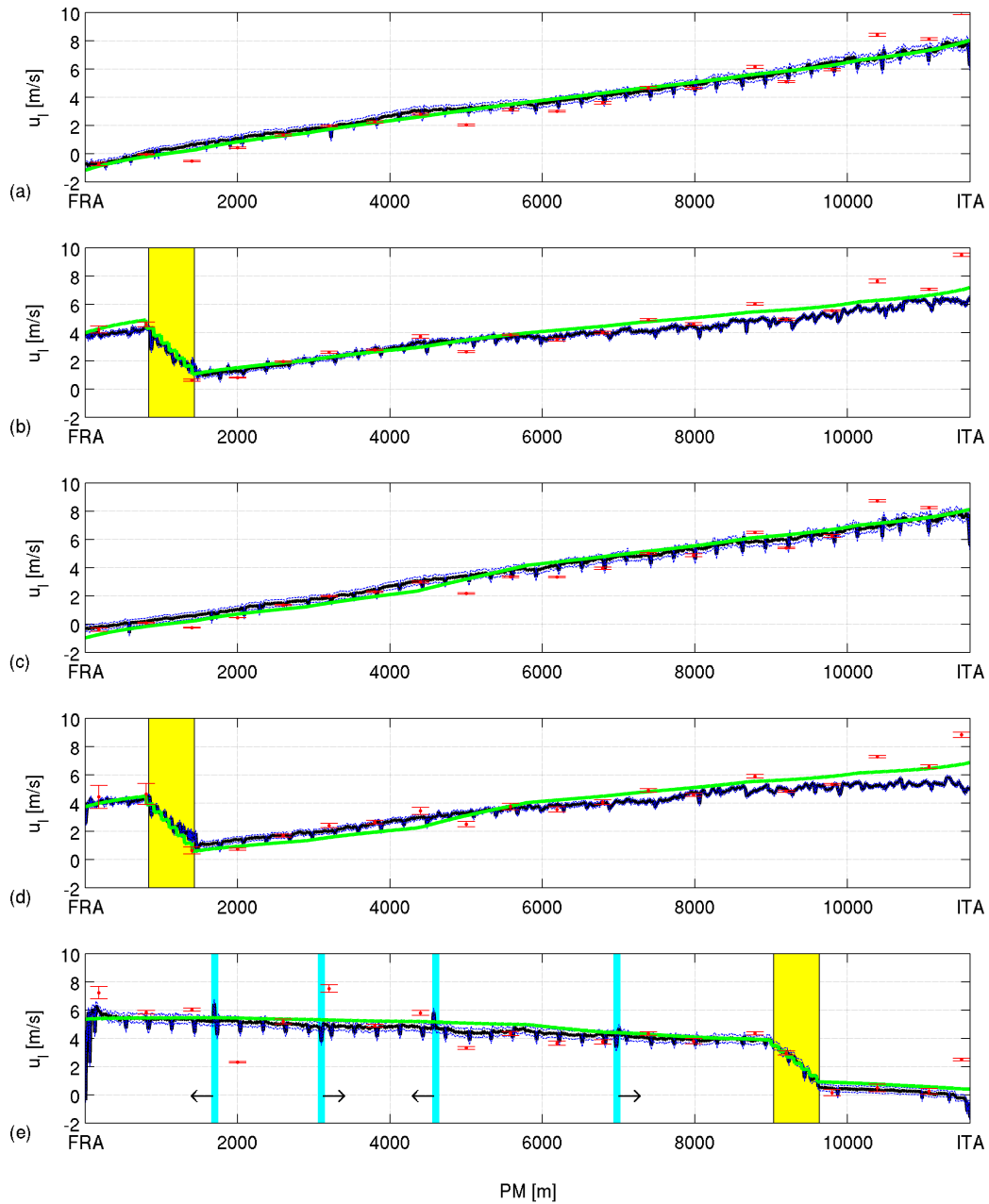
In Figure 2 the tunnel air velocity profile, as calculated by the calibrated model, is plotted in green. The black line is the velocity profile as measured by Levoni et al. [16]. Red dots with errorbars represent pointwise measurements taken by the fixed anemometers permanently installed in the tunnel, for the sake of further comparison. The background is coloured in yellow along the 600 m section in which the extraction vents are open, in case the extraction system is active. The tunnel streaks in which a jet-fan couple is active are highlighted by a blue background, along with an arrow indicating its direction.

The model response to the calibration process is quite encouraging, as it can be appreciated at Figure 2. Although the calculated velocity profile slightly differs from the measured profile, especially within the cases in which the extraction system was turned on, the overall profile shape and slope changes are caught precisely.

Parameter	Value	Unit	Case id	RMS deviation [m/s]
$\epsilon_{AF}$	2.81	mm	1	0.21
$\epsilon_{AV}$	6.98	mm	2	0.46
$\beta_{trap,open}$	101	-	3	0.34
$\beta_{trap,shut}$	$5.18 \times 10^4$	-	4	0.64
$\beta_{vent}$	20.2	-	5	0.36

**Table 3.** Calibrated parameter set (left), RMS deviation for each of the 5 cases (right).





**Figure 2.** Comparison between calculated velocity profile (green), measured velocity profile (black) and pointwise velocity measurements taken by the tunnel anemometers (red).

It has to be mentioned that velocity measurements close to the Italian portal have been found to be affected by a severe noise: this can be partially evinced by the deviation between present experimental data and the values given by the fixed anemometers. Such region is also characterized by the highest deviation between numerical results and benchmark measurement data.

## 6. Concluding remarks

A model for the prediction of ventilation flows in road tunnels has been developed, under the hypothesis of 1D, steady-state flow, based on a modified version of the SIMPLE algorithm. Details of the discretization procedure have been reported, along with the main strategies adopted to treat source and sink terms. Friction parameters which remained unknown a priori have been calibrated on the basis of an experimental dataset collected throughout five in situ tests performed at the Mont Blanc Tunnel, which provided the entire longitudinal velocity profile along the tunnel by means of a custom-made survey rake moving at a strictly constant velocity survey.

The DES (Derandomized Evolution Strategy) has been used for the estimation of the values of two equivalent roughnesses and three equivalent concentrated loss coefficients, on a 1D model network with a spatial resolution of 10 m. With the optimized parameter values, the predicted velocity profiles agree well with the experimental data, with an overall RMS deviation of  $\pm 0.42$  m/s. Given the complexity of the model, and the relatively low number of variable loss coefficients, the obtained accuracy has to be regarded as satisfactory. Further refinements of the model could include an increase in the number of variable parameters, in order to obtain an even better matching with the benchmark data. Finally, it has to be mentioned that the calibrated model should be tested against further field data other than the benchmark cases, to completely validate its applicability to the real-world system.

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