Automated coupling of standard one-dimensional and three-dimensional flow solvers for simulation of metro ventilation systems

Y Scott Shi, C Fleming, C Sejekan, E Wong, M Samimi, M Duckham
SNC-Lavalin Inc., Canada

ABSTRACT

With increased globalization and the exponential growth of human population, underground transit systems have become a necessity in metropolitan areas around the world. In addition, there is an increasing awareness of human comfort and safety inside these complex structures, and the need for accurate numerical modelling and analysis has become a priority as part of the design process. This modelling is generally carried out both network-scale and station-scale. Network-scale phenomena include the piston effect of trains, longitudinal ventilation of tunnel fires, and the long-term thermal absorption of the tunnel lining and surrounding soil. One-dimensional network flow solvers are well-suited to network-scale modelling. Station-scale flow features include smoke migration through stations as well as flow separations and their corresponding pressure losses. These complex flows necessitate more sophisticated three-dimensional flow solvers. As the two scales are highly interdependent, achieving good consistency between the 1D and 3D models is essential especially since the boundary conditions for the 3D models are most often supplied by the 1D runs. However, the complicated 3D designs rarely translate well into accurate 1D models. Thus, the simplification and assumptions made while creating the models introduce inconsistencies. In this article, a novel coupling approach is proposed to mitigate these inconsistencies by optimizing the local pressure loss coefficients within the 1D models. This approach is validated and tested on representative station models. Results promise better flow distribution and prediction using the 1D model. Furthermore, this coupling method would not just be limited to 3D computational data but could also be used with field measurements.

1 INTRODUCTION

Metro ventilation system designs are typically verified at the design stage using numerical models. Modelling is generally carried out at two scales: network-scale and station-scale. Network-scale phenomena include the piston effect of trains, longitudinal ventilation of tunnel fires, and the long-term thermal absorption of the tunnel lining and surrounding soil. 1D network flow solvers such as the Subway Environmental Simulation (SES) Program [1] are well-suited to network-scale modelling, and provide predictions of flow rates and temperatures which are adequate for network design purposes (refer to the validation cases reported in the SES User Manual [1] for examples). Station-scale flow features include smoke migration through stations as well as flow separations and their corresponding pressure losses (e.g. through doors and stairways). These complex flows necessitate more sophisticated 3D flow solvers, which may be based on Reynolds-averaged or filtered formulations of the Navier-Stokes equations.

Station-scale and network-scale flows are interdependent: the local flow pattern within a station is influenced by train motion and fan operation within the wider network, and air flow at the network scale is influenced by local pressure losses within stations. 1D and 3D numerical models of a metro system should be consistent with one another to reflect this interdependency of scales. Boundary conditions at tunnel interfaces in a 3D station model should represent the influence of the wider network. Local pressure losses in a 1D network model should reflect the actual pressure losses at corresponding locations in the 3D station model. This is a straightforward task for tunnel flows, where local losses for simple expansions, contractions and branches can be determined via coefficients based on experimental data [1, 6]. Difficulties arise for flow through more complex geometries such as metro stations, where experimental reference data is not available. It is often unclear how best to represent 3D features such as stairways, fare gates, escalator shafts or smoke baffles in a 1D model, and what values the corresponding loss coefficients should take.

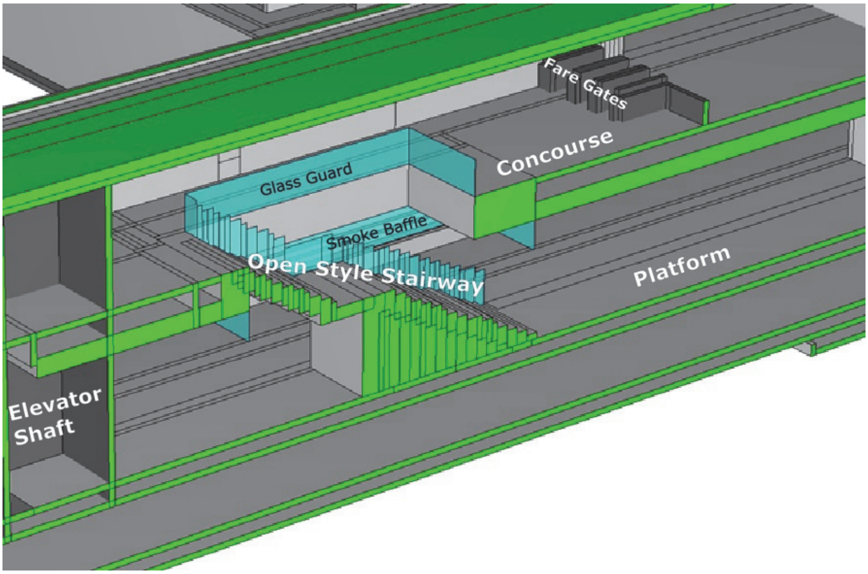

Figure 1. Example of an open staircase (side section view)

As illustrated in Figure 1, the pressure loss through an open-style stairway is difficult to interpret as an equivalent pipe flow pressure loss. One approach would be to interpret the system as a combination of two turning elbows and an orifice. However, the elbows are ill-defined and hence their losses are difficult to determine from standard references. Additionally, there is an interaction effect between the three elements which must be accounted for. Prince et al [2] used a 3D computational fluid dynamics (CFD) model to demonstrate that the pressure loss across a duct with two elbows depends on elbow orientation, and the interaction effect depends on elbow separation distance. They found that 3D CFD can predict the pressure losses along complex flow paths reasonably well.

Another modelling approach for metro systems is to use a fully coupled 1D/3D flow solver, such as those developed by Collela [3] and Prince [4]. These methods, based on modified versions of the 3D flow solvers ANSYS Fluent and OpenFOAM respectively, directly calculate the local pressure losses at the station-scale, and automatically update boundary conditions at 1D/3D interfaces based on events at station-scale and network-scale. Of course, the successful calculation of complex pressure losses using a 3D numerical model is dependent on its quality and accuracy, the discussion of which is beyond the scope of this paper. Additionally, there is a significant computational cost associated with the 3D portions of the model. Hence, it is not suitable for network-scale modelling.

An alternative method of 1D/3D model coupling was developed using (but not limited to) standard versions of SES and the 3D flow solver Fire Dynamics Simulator (FDS) [5]. The method involves using an isothermal 3D CFD model to determine the pressure losses and flow rates in complex areas of the network (i.e. within stations) and adjusting the loss coefficients in an equivalent 1D model until local flow rates and pressure losses are matched. It is worth noting that this method could also utilize field measurements instead of 3D CFD predictions.

The resulting 1D network model has a reasonably accurate representation of stations, and therefore in addition to predicting network-scale flows with good confidence it is a useful and fast indicator of potential design failures at station-scale. Station-scale design scenarios, such as platform fires, are first simulated using the 1D model, and boundary conditions for subsequent 3D models are determined. The resulting 1D model also benefits network-scale non-emergency simulation where more accurate local air flow rate in stations will help determine potential violation of air velocity criterion. Furthermore, the model can be used to better predict air flow during testing and commissioning phase.

2 METHODOLOGY

The method begins by constructing similar 1D and 3D isothermal models of the station of interest. Figure 2 is an example of a typical station. The 1D model (solid black lines and dots) includes all the flow paths which exist in the 3D geometry as illustrated in Figure 3.

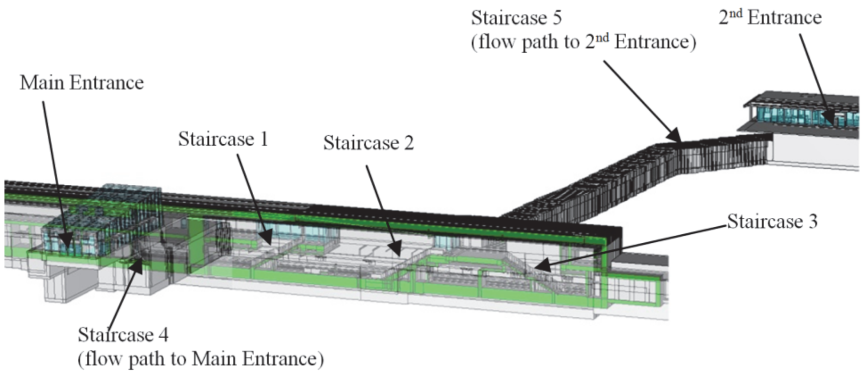

Figure 2. 3D schematic diagram of a typical metro station

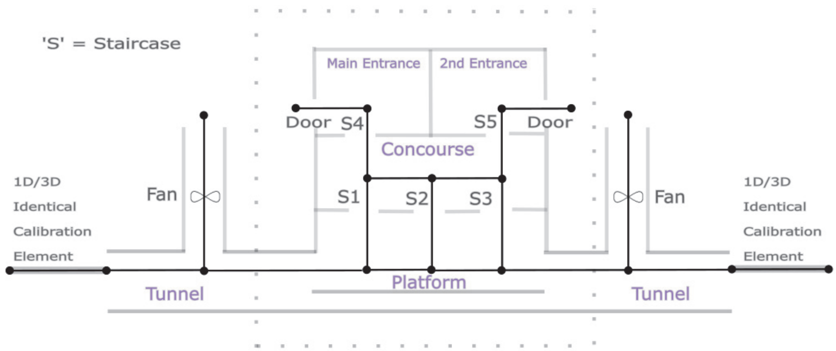

Figure 3. 1D model overlaid on a simplified schematic representation of a metro station. The dotted line indicates the portion of the station shown in Figure 2

Utilizing the advantage of the simple 1D modelling capability of FDS 6.5.2 [5], 1D elements of known hydraulic resistance are added to represent tunnels connecting to the station. Identical elements are included in the 1D SES model. The resistances of the adjoining 'calibration' elements are set such that there is an approximately even balance of flow from the calibration tunnel side and station side of each ventilation shaft, in order to guarantee a reasonably sufficient air flow through all of the station stairways and calibration elements. The general exhaust flow directions are indicated in Figure 4.

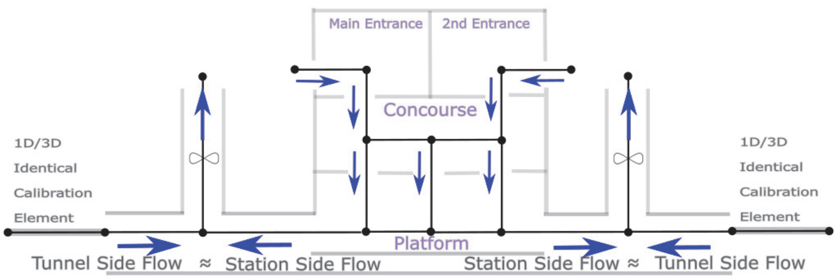

Figure 4. General flow directions in each 1D section when the ventilation system is operating in exhaust mode

The inclusion of the calibration elements is important as it allows both the flow rate and pressure drop to be matched. If 1D air flow predictions were prescribed at the tunnel boundaries, the 1D model could match the flow rates of the 3D model with an arbitrary set of local loss coefficients which are correct relative to one another but too high or too low in an absolute sense, i.e. the overall pressure drop through the station could be over- or under-predicted.

The 3D model is used to simulate isothermal flow through the station with the ventilation system in supply or exhaust mode (as shown in Figure 4). The same scenario is then simulated in the 1D model with estimated local loss coefficients. In an automated routine, the flow rates along selected paths are compared, the corresponding loss coefficients are adjusted through a proportional-integral-derivative model, and the 1D simulation is repeated. Ultimately, loss coefficients are determined for each flow path in the 1D model, such that differences in the local flow rate are within a certain tolerance. The procedure is repeated with the ventilation system operating in the opposite mode (i.e. supply or exhaust) and then for each station in the metro network.

3 DEMONSTRATION AND DISCUSSION

3.1 Complexity of a simple geometry with obstructions

To demonstrate that the pressure loss can be difficult to predict even for simple obstructions, two models are set up in SES and FDS as shown in Figure 5 and Figure 6.

Each model consists of an inlet with a steady inflow. The inlet path is then divided into two branches with identical cross section and length. The 'reference' branch has a wall friction loss and an exit loss. The obstructed branch is similar, but features additional unknown losses due to an elbow junction and several full-height rectangular column obstructions.

In the first model (Figure 5) the obstructed branch features three equi-spaced columns upstream of the elbow. The second model (Figure 6) features three additional equi-spaced columns downstream of the elbow.

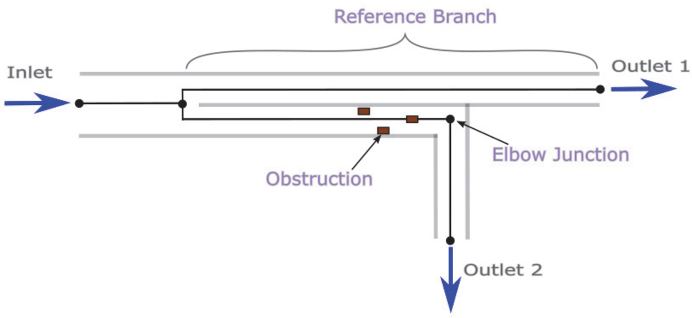

Figure 5. Simple geometry containing three obstructions

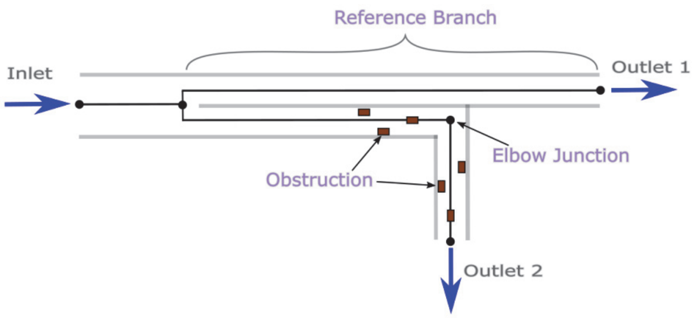

Figure 6. Simple geometry containing six obstructions

The new iterative coupling method is used to determine the pressure losses for the obstructed branch of each model. The corresponding loss coefficient, or *K*-factor, is defined as

$$K = \frac{\Delta p}{\frac{1}{2}\rho u^2} \tag{1}$$

where Δp is pressure change, ρ is density and u is velocity. *K*-factors of 1.74 and 3.3 are determined for the obstructed branch in the three-column and six-column case, respectively. For comparison, the branch loss is calculated from reference data as the sum of the separate friction, elbow, exit, and column losses in Table 1, which are significantly different to the numerical predictions.

Table 1: Calculation of obstructed branch *K*-factor based on reference data

Element	*K*-factor	Sources
Walls (friction)	0.13	Based on Darcy friction factor of 0.026
Elbow	1.5	SES User's Manual, Table 4.4 [1]
Single column	1.52	SES User's Manual, Table 4.3 [1]
Exit	1.0	SES User's Manual, Table 4.4 [1]
Total – 3 column case	7.19	
Total – 6 column case	11.75	

The situation in a metro station is more complex with columns, escalator shafts, fare gates, and smoke baffles in close proximity as shown in Figure 1. Hence a 3D CFD prediction of the pressure loss is expected to be more reliable than a simplified calculation in the style of Table 1.

3.2 Calibration element

The 'calibration' element, the common element between the 1D and 3D models shown in Figure 4, ensures that flow rates and hydraulic resistance are matched. To demonstrate the concept, a simple symmetrical model was set up in both SES and FDS as shown in Figure 7. Flow rates of 50-100 m^3/s were specified at the ventilation shaft, and the *K*-factors in element 1 and 2 were varied. For cases where both *K*-factors are below approximately K= 20, SES and FDS predictions of flow rates Q_1 and Q_2 do not agree, due to modelling differences in the wall friction between 1D and 3D models. However, the pressure losses in metro stations are dominated by large-scale flow separations at stairways and other obstructions, and that wall friction is less significant. When $K_1 > 20$ and $K_2 > 20$, SES and FDS predictions of flow rate and pressure drop agree very well, with the error generally below 1%.

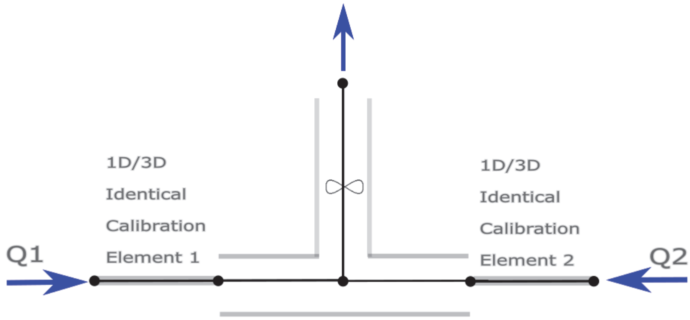

Figure 7. Simple demonstration of the 1D/3D calibration elements

3.3 Application to metro stations

In this section, the effect of matched 1D and 3D models of a typical metro station (illustrated in Figure 2) is demonstrated. In the first case *K*-factors for the 1D model are prescribed based on guidance from the SES User's Manual [1]. This results in an approximately symmetrical air flow pattern on the platform level as indicated by the schematic vectors in Figure 8 (where arrow size indicates approximate relative flow rate).

The new coupling method is then used to determine the *K*-factors, such that the flow rates in each path are within 3% of the reference 3D simulation. An asymmetric flow pattern develops, as shown in Figure 9, reflecting geometrical differences in the various stairways and entrances.

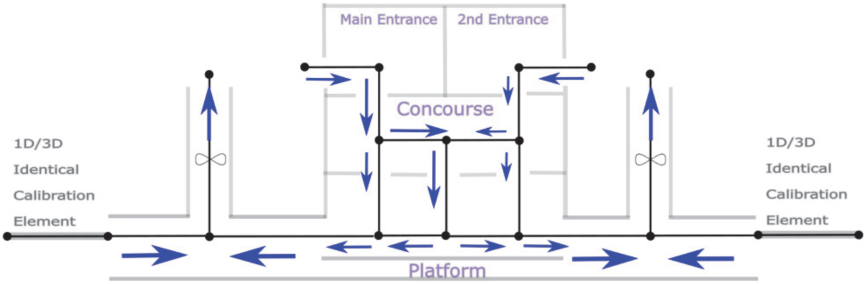

Figure 8. 1D flow pattern based on *K*-factors from reference data

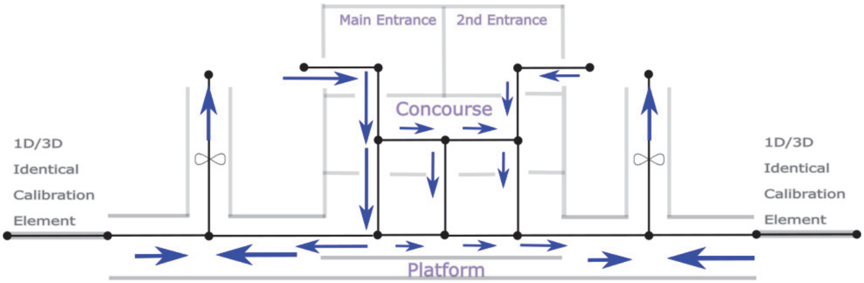

Figure 9. 1D flow pattern based on *K*-factors determined by matching the 3D reference simulation

Comparing Figure 8 and Figure 9, the magnitude and location of the highest air flow rate has changed, as well as the locations of flow split on the platform and the concourse. These changes can have significant effects on predicting both normal and emergency operations with the optimized model.

1. Normal operation:

   The optimized model can better predict where air velocity may exceed the criteria within stations. With better predictions of the air flow pattern, more reliable temperature predictions may be made.

2. Emergency operation:

   The optimized model can better predict the air flow pattern and hence smoke migration (indicated in SES by temperature). Tunnel emergency fire cases can also benefit from the coupled model, due to improved modelling of the hydraulic resistance of adjacent stations. Additionally, optimized 1D model is a fast and approximate indicator of potential design failures for station fire scenarios, which can subsequently be examined in detail using the 3D model.

4 CONCLUSION

A new method of achieving consistency between 1D and 3D models of air flow in metro systems using standard versions of widely-used flow solvers was developed. Such consistency is necessary to adequately represent the hydraulic resistance of stations in network-scale 1D models, and to adequately represent network-scale effects in station-scale 3D models.

Other authors have addressed this issue by implementing 1D tunnel flow models within existing 3D flow solvers, thereby achieving fully-coupled 1D/3D simulation capabilities. However, these methods did not improve 1D modelling accuracy. Our method improves the accuracy of 1D network-scale models of normal operations and of tunnel fires with better representation of station resistances. The optimized 1D model is also used to determine boundary conditions for its 3D counterpart during a station fire scenario. Moreover, our method is based on standard versions of existing 1D and 3D software and hence avoids considerable development and validation efforts. The 3D flow solver FDS 6.5.2 was used to calculate the flow through a station in isothermal conditions, and this flow was matched by automatically adjusting the pressure loss coefficients of an equivalent 1D flow model designed in SES v4.1.

As a final note, the 1D model could be tuned to match field measurements instead of 3D simulation results, which might be useful for modelling the impact of refurbishment or extension of existing systems.

REFERENCES

[1] Subway Environmental Simulation Computer Program SES Version 4.1, Part I user's Manual, New York: US Department of Transportation, 2002.

[2] J Prince, M Tabarra, J Alexander, J Peiro, "On the prediction of pressure losses in complex flow scenarios using CFD," in *16th International Syposium on Aerodynamics, Ventilation & Fire in Tunnels*, Seattle, USA, 2015.

[3] Francesco Colella, Vittorio Verda, Romano Vorchiellini, Guillermo Rein, "One-dimensional and multi-scale modelling of tunnel ventilation and fires," in *Handbook of Tunnel Fire Safety*, ICE Publishing, 2012, p. 541–554.

[4] J. Prince, "Coupled 1D-3D simulation of flow in subway transit networks," Imperial College London, 2016.

[5] K. McGrattan, S.Hostikka, R.McDermott, J.Floyd, C.Weinschenk, K.Overholt, Fire Dynamics Simulator User's Guide, 6th ed., National Institue of Standards and Technology, 2017.

[6] D. Miller, Internal Flow Systems., BHRA Fluid Engineering, 1978.