EMISSION MANAGEMENT IN RAILWAY TUNNELS WITH A 1D-3D SIMULATION APPROACH

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ABSTRACT

Railway tunnel maintenance involving grinding operations poses a significant challenge due to the emission of hazardous exhaust gases and dust, making the tunnel an unsafe working environment for personnel. To address this issue, simulations become crucial for designing and operating an efficient tunnel ventilation system, essential to mitigate these risks. The simulation workflow outlined in this paper brings together a fast and quasi-real time 1D systems model approach with a detailed 3D Computational Fluid Dynamics (CFD) simulation. This approach not only predicts the duration required for the dust and exhaust levels to reach acceptable safety thresholds, but also assesses the energy consumption of a given ventilation system. This study eventually underlines the ease and speed with which different scenarios can be tested, emphasizing how accessible this approach is without requiring extensive simulation expertise from end-users.

Keywords: CFD, system modelling, railway tunnel emission management, railway tunnel ventilation, rail-grinding

1. INTRODUCTION

Rail grinders are track maintenance vehicles used to restore the profile of rails and eliminate irregularities, contributing to prolonging the lifespan of rails and improving the overall performance of trains. However, when operating within tunnels, these vehicles emit exhaust and dust, posing health risks to workers. The variety of diesel and petrol-powered vehicles, machinery, and tools used in such scenarios emit harmful emissions that can lead to severe respiratory and cardiovascular diseases [1]. In addition, maintenance activities on the ballasted superstructure generate hazardous dust emissions, including mineral and quartz dust, potentially leading to lung disorders such as silicosis or even lung cancer [1]. Prioritizing the safety and well-being of tunnel personnel requires the ability to predict the duration needed for emissions to diminish within the tunnel environment, while utilizing a ventilation system. Furthermore, accurately estimating the energy consumption requirements for a ventilation system is crucial in mitigating these risks efficiently.

In this context, simulation emerges as a key tool in the design and operation of an efficient ventilation system, especially in cases where conducting experiments on a large number of tunnels is not feasible; such as in the case of the expansive German railway tunnel infrastructure spanning over 33,500 km [2]. The proposed 1D-3D simulation approach stands as a sophisticated methodology to address the challenges posed by rail grinder emissions in tunnels. While 1D simulations offer speed and simplicity, they may lack accuracy without proper calibration derived from measurement or simulation data, making it challenging to obtain reliable results. On the other hand, 3D simulations provide high-fidelity results with reasonable computational effort in areas in proximity to the train, which can be used to calibrate 1D models. By combining the strengths of both 1D and 3D simulations, both resources are used efficiently, ensuring a balance between computational effort and accuracy of results. This approach not only offers an intelligent solution for railway tunnel design and operation, but also makes final simulation tool accessible to individuals without extensive simulation expertise, thereby promoting a more inclusive and democratized approach to simulation.

This paper begins with an overview of the 1D-3D concept, followed by a comprehensive case study that thoroughly outlines each step of the workflow. Finally, the conclusion and summary of this work are drawn in the last section.

2. CONCEPT

An overview of the simulation workflow is shown in Figure 1. In the first stage, SIMULIA PowerFLOW®, a Lattice Boltzmann Method (LBM) solver, is employed to generate a 3D CFD model. LBM solver operates by solving the mesoscopic Boltzmann equation to predict macroscopic fluid dynamics. This solver is high-fidelity transient and compressible, exhibiting very low numerical dissipation. Additionally, the LBM solver is equipped with an integrated Lagrangian particle simulator that can simultaneously track millions of particles with highly detailed models. Transient particle trajectory tracking is crucial, as it facilitates the mixing of particles, captures airflow fluctuations, and ensures accurate dispersion analysis. Following the 3D simulation, an advanced post-processing analysis follows. This step allows to extract volumetric and surface results essential for the proper calibration of the 1D model.

The third step involves the development of a calibration model in CATIA Dymola®, which utilizes Modelica®, an open-source object-oriented language for modeling complex physical systems. Replicating the 3D scenario in a 1D model and obtaining precise calibration parameters, the workflow processes for preparing and executing the 1D long tunnel model. In the fourth step, a realistic simulation scenario of a long tunnel and its ventilation system is defined, which is executed in a matter of seconds, allowing rapid tuning and testing of the model in a short time frame. Upon completing the 1D simulation, the workflow moves to the fifth step, wherein the results are post-processed to estimate the development of emissions over time and assess power consumption attributed to the ventilation system. The final step includes the option to rerun the 1D model for different simulation scenarios. This can be achieved either using CATIA Dymola® or within the 3DEXPERIENCE® platform, which offers a comprehensive business and product development framework, enabling non-experts to leverage an advanced simulation process such as the one outlined in this paper.

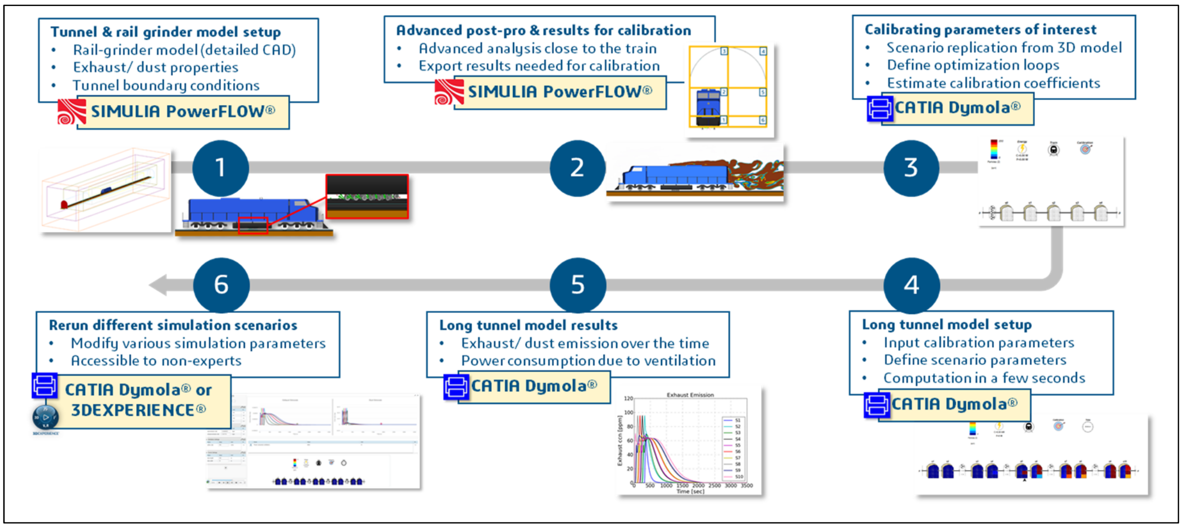

Figure 1: 1D-3D simulation approach overview

3. CASE STUDY

This section presents step by step a case study of a railway tunnel during grinding operations, demonstrating its applicability and effectiveness in real-world scenarios.

3.1. 3D CFD model: Tunnel & rail grinder model setup

An overview of 3D CFD tunnel and rail grinder model is shown in Figure 2. In this particular use case, a detailed 3D CFD simulation is prepared for a 200 m long tunnel. This includes a train model equipped with a grinder featuring 6 cylinders representing grinding stones, operating at a speed of 10 km/h. At the tunnel entrance, the inlet velocity boundary condition is set at 4.95 m/s, considering the airflow generated by the ventilators. This condition assumes a uniform flow distribution in the tunnel, neglecting potential flow concentration near the ventilators as well as velocity variations from top to bottom of the tunnel. To simulate exhaust emissions, vapor water scalar transport modelling is chosen, which is coupled with the flow solver. The mass flow rate of the exhaust emissions at the outlet is set to 27 g/s. For dust emissions, particle modeling is employed, incorporating two types of dust particles, A- and E-dust, characterized by mean diameters of 1.5 and 6.25 µm, respectively. The dust emission rate is determined to be 12,000 particles per second. To properly discretize the domain, 6 variable resolution (VR) levels are used, as shown in Figure 3, whose resolution is increased by a factor of two compared to the neighboring area, with the finest resolution applied at the emitter area and exhaust outlet equivalent to 6 mm.

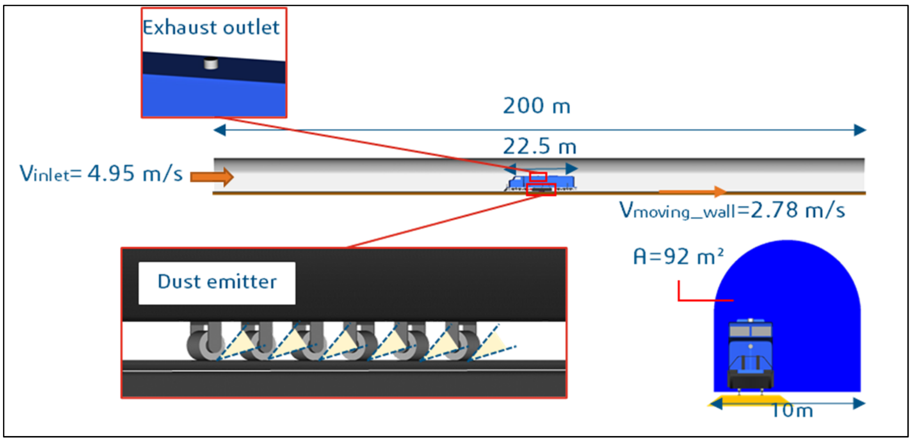

Figure 2: Overview of 3D CFD model.

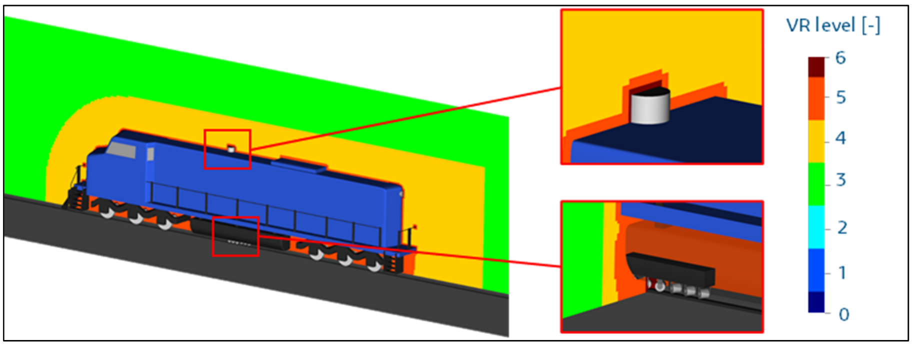

Figure 3: Close-up view of variable resolution (VR) levels.

3.2. 3D CFD model: Advanced post-pro & results for calibration

Figure 4 shows an example of the comprehensive post-processing analysis that provides insights into the dispersion of emissions in close proximity to the train. First, plotting the total pressure plane across the train helps to understand the wake dynamics. To complement this, an iso-surface plot provides a more intuitive representation of its structure. The accurate prediction of the train's wake is essential for understanding the dispersion and transportation of exhaust gases and dust particles within the surrounding airflow. This region significantly influences the propagation patterns of these particles, thus affecting their distribution and motion. Moreover, instantaneous results of the exhaust gas mass fraction are shown through both cut plane and volumetric representations. Additionally, similar to exhaust emissions, to offer a more intuitive understanding of the dust dispersion, volumetric results of particle volume ratio are presented.

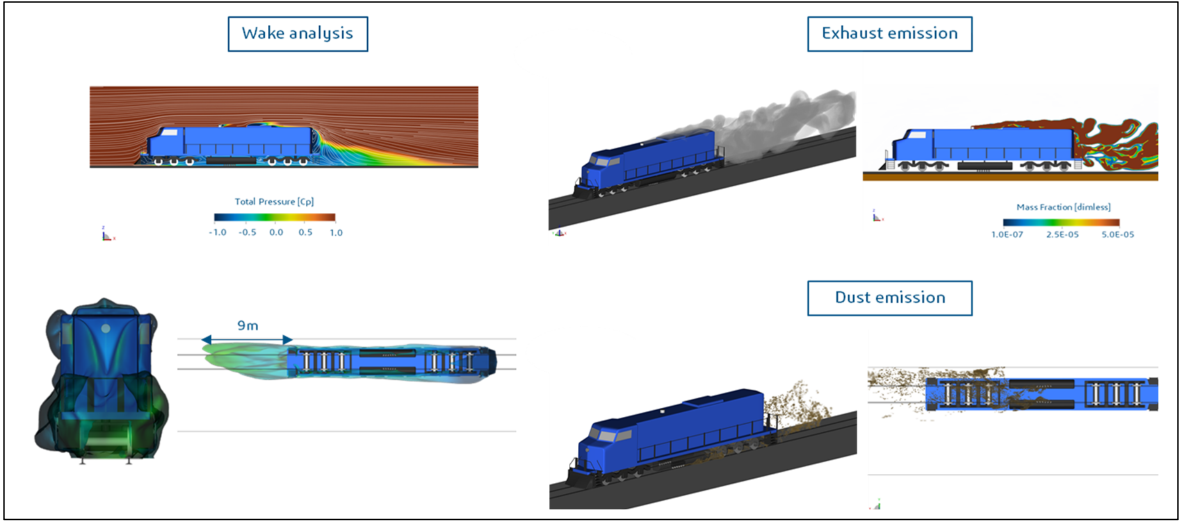

Figure 4: Advanced post-processing of 3D CFD analysis.

Regarding the calibration of the 1D model, certain quantitative results have to be extracted from the 3D CFD simulation that capture the main flow patterns. These results include volumetric mean data of the total concentration of exhaust and dust emissions across 18 volumes shown in Figure 5, as well as, surface results of mean mass flow and static pressure on the interfaces between the volumes for mean mass flow and static pressure. The results of the mass flow and exhaust gas concentration are given as examples in Table 1 and Table 2 respectively.

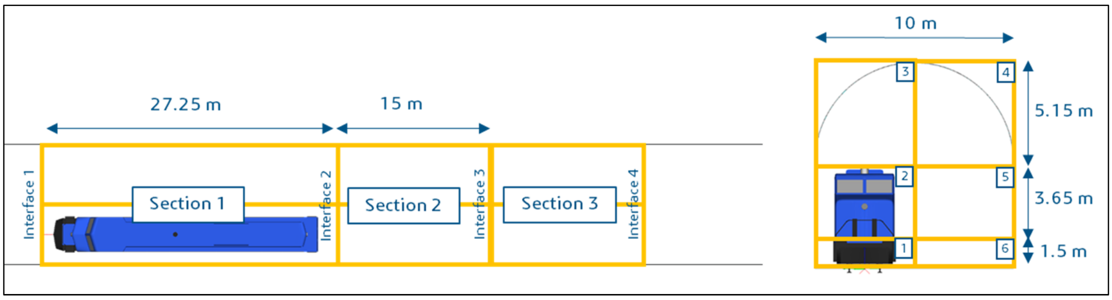

Figure 5: Sections and interfaces to extract results needed for calibration.

Table 1: Mean mass flow [kg/s]

Surface	Interface 1	Interface 2	Interface 3	Interface 4
1	40.7	14.6	26.1	30.2
2	104.0	81.7	92.5	98
3	123.5	138.9	133.4	129.6
4	126.0	140.5	134.3	132.2
5	111.7	126.0	119.8	118.3
6	44.9	49.7	45.1	43.0

Table 2: Mean exhaust emission concentration [ppm]

Surface	Section 1	Section 2	Section 3
1	7.2	183.0	242.4
2	158.4	348.2	290.4
3	104.3	22.5	21.6
4	0.1	0.1	0.3
5	0.1	2.9	5.2
6	0.1	4.4	23.9

3.3. 1D system model: Calibrating parameters of interest

Implementing the 1D model for parameter calibration requires the replication of the 3D use case scenario, which is essential for achieving a consistent correlation between two distinct approaches. Figure 6 shows the 1D system modeling of the tunnel used to calibrate the parameters of interest. In this process, each segment of the 1D model corresponds to a specific part of the 3D model. Within each 1D slice, 6 nodes are defined, facilitating flow in different directions while identifying the exact locations where exhaust or dust emissions occur. Defining boundary conditions similar to those in the 3D model involves configuring inputs, such as train speed and airflow ventilation. These elements play a critical role in ensuring the match between the 1D and 3D models.

The technical complexities of the calibration process include identifying specific parameters to be adjusted. Parameters of interest include flow coefficients, not only for the main flow but also for perpendicular directions, the train's wake length, and the rate at which dust and exhaust emissions dissipate. To fine-tune and optimize the model, a series of iterative optimization loops are deployed. These loops are essential in calibrating and adjusting pressure dynamics, the distribution of mass flow, and the overall quantity of dust suspended in the air.

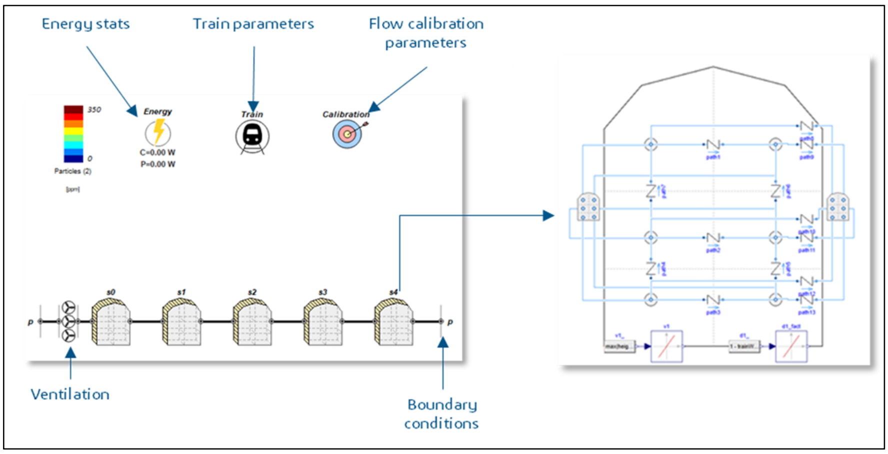

Figure 6: 1D system modeling of the tunnel for calibration flow parameters.

3.4. 1D system model: Long tunnel model setup

The 1D system model for a long tunnel scenario is subsequently developed. Figure 7 shows a schematic representation of 1D model of the long tunnel case. Here, the model employs 4 ventilators distributed across the 1 km long tunnel, with each 1D segment representing a 100 m section. Boundary conditions are defined at the entrance and exit of the tunnel, and specific inputs for the train, such as its length, speed, and rates of dust and exhaust emission, are incorporated, along with the calibration parameters estimated from the previous step.

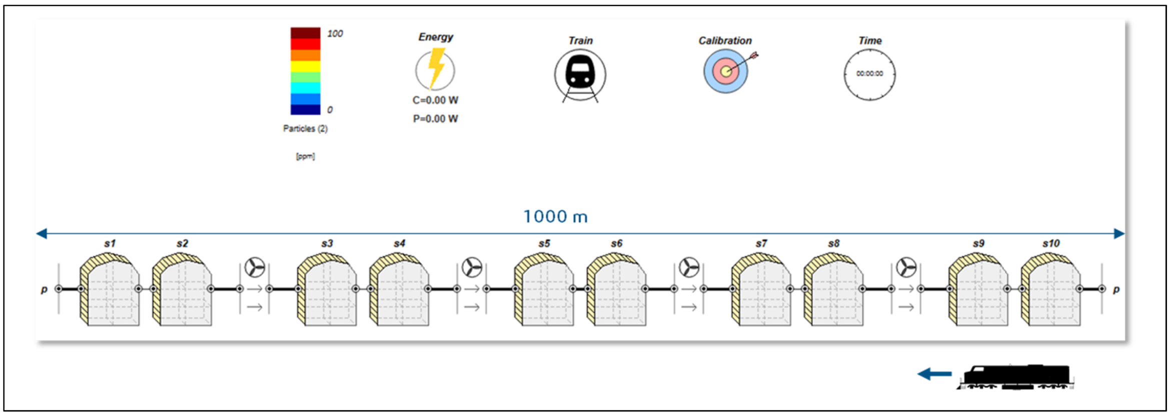

Figure 7: 1D system model of the long tunnel model.

3.5. 1D system model: Long tunnel model results

Monitoring exhaust and dust emissions across various tunnel sections over time is crucial as it helps to ensure a safe working environment. Figure 8 shows the exhaust and dust emissions over the time per tunnel slice. In particular case, it takes approximately 30 minutes for the exhaust gas concentration to diminish significantly, reaching a notably low level within this timeframe. However, the dust concentration tends to decrease at a faster rate, due to gravity. Furthermore, an additional aspect under consideration is the estimation of the energy consumption attributed to ventilation, which for approximately half an hour of operation in this case is estimated at 3.64 kWh. This assessment broadens the scope of understanding regarding the operational costs and environmental impacts associated with maintaining optimal air quality in such infrastructure.

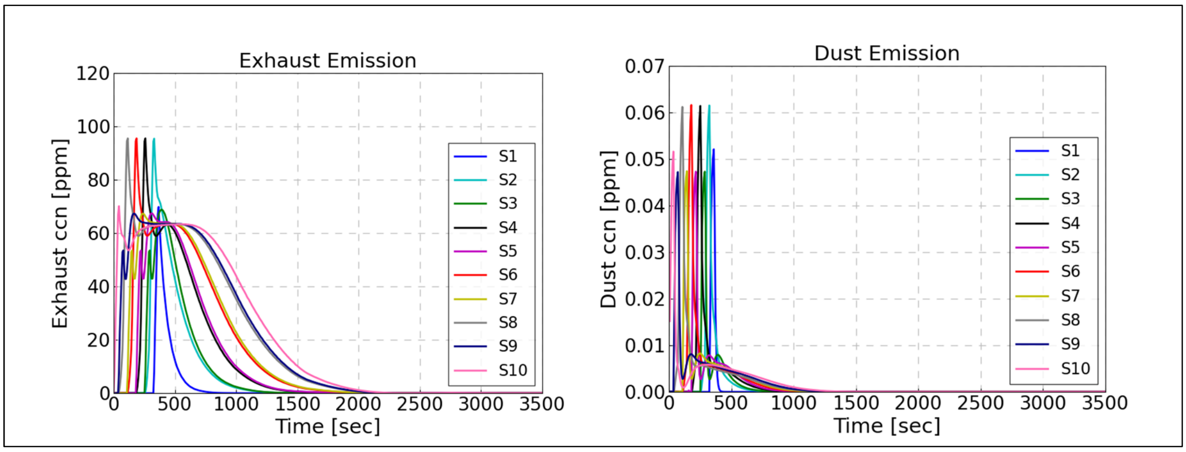

Figure 8: Exhaust and dust emission concentration over the time per tunnel slice.

3.6. 1D system model: Rerun different simulation scenarios

As previously highlighted, the end-user has the capability to efficiently rerun the 1D long tunnel model within a matter of seconds in CATIA Dymola® or the 3DEXPERIENCE® platform. Particularly in the platform through the dedicated role System Simulation Design, users can easily interact with the model. This allows them to modify various parameters such as train length, speed, dust and exhaust rates, rerun simulations, and review the results.

Therefore, the challenge in enabling non-experts to take full advantage of the capabilities of an advanced simulation process can be achieved in the platform through a streamlined approach including the following key aspects:

- **Effortless access**: Using the platform is as simple as opening a web browser, eliminating the need for complex software installations.
- **User-friendly interface**: A sophisticated, user-friendly cockpit displays only the essentials for easy navigation. Figure 9 shows an overview of the simulation dashboard within the platform.
- **Simplified parameter selection**: Selecting model variables, aligned with non-expert understanding, empower users to define only crucial parameters without complexity.
- **Simplified post-processing**: Graphical representations provide clear insights, such as emissions per tunnel segment and power consumption, without overwhelming technical details.

Railgrinder Settings

Name	Value	Unit	M...
vehicle cross area	8	m2	
vehicle length	22.25	m	
vehicle speed	2.778	m/s	
vehicle initial position	0	m	

Emission settings

Name	Value	Unit	M...
dust emission rate	0.0000633	kg/s	
exhaust emission rate	0.02719	kg/s	

Ventilation Settings

Name	Value	Unit	M...
airflow rate	100	m3/s	

Tunnel Settings

Name	Value	Unit	M...
slice length	100	m	
slice width	10	m	

Name	Value	Unit	M...
Power consumed (ventilation)	6552	W	

Figure 9: Web-based railway tunnel simulation dashboard on the 3DEXPERIENCE® platform.

4. CONCLUSION

In summary, this work shows the effectiveness of a combined 1D-3D simulation approach to address the complex problem of managing exhaust and dust emissions in railway tunnels during grinding operations. The 3D CFD simulation not only provides insights into exhaust and dust dispersion in proximity to rail grinder, but also plays a crucial role in calibrating the 1D model properly. The 1D system simulation proves instrumental in estimating tunnel cleaning duration and determining the energy consumption of ventilation system in a 1 km long tunnel scenario. Notably, leveraging the 3DEXPERIENCE® platform is an excellent example of democratizing simulation, making it accessible to a wider audience. While the presented case study focuses on a specific ventilation and tunnel design, a key future step involves employing 3D CFD to model multiple layout scenarios alongside well-tuned 1D models. This comprehensive approach would enable non-experts to explore a variety of tunnel and ventilation designs, thereby significantly enhancing tunnel performance in terms of both safety and energy efficiency. Furthermore, the assumption of a uniform flow distribution in the 3D CFD model setup, discussed in Section 3.1, lays the groundwork for future exploration, potentially expanding this approach to analyze ventilator spacing. Looking ahead, the focus is on acquiring measurement data to further refine and validate the simulation models against experimental data, marking the next step in enhancing the accuracy and reliability of the simulation approach.

5. REFERENCES

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