

THE KORALM TUNNEL AS A REAL-WORLD LABORATORY: RESEARCH WORK AND FINDINGS DURING THE CONSTRUCTION OF THE KORALM TUNNEL

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ABSTRACT

The Koralm Tunnel (KAT) was used as a real-world laboratory during the mechanical equipment phase and commissioning in order to investigate a range of operational, safety-related, and aerodynamic phenomena under realistic high-speed railway conditions. A series of coordinated experimental and measurement campaigns were conducted to generate data relevant for tunnel design validation, system commissioning, and future tunnel projects.

Dust exposure levels were investigated during high-speed train movements to assess occupational safety conditions and to evaluate particle transport mechanisms within the tunnel system. Based on these measurements, the service life of ventilation and technical room filters was determined under representative operating conditions. Pressure loads induced by train passages were measured both in the tunnel and within adjacent technical rooms, providing insight into transient pressure propagation and structural loading of technical installations.

The behaviour of pantographs during high-speed operation investigated using CFD simulations in order to determine the contact force between the pantograph head and the fixed catenary. The aim is to use this information to prevent arcing and burn marks on the the fixed catenary. In parallel, wall friction was determined using pressure and velocity measurements, contributing to an improved understanding of resistance effects relevant for ventilation design and energy demand. Aerodynamic processes in the cross passages and the underground evacuation and rescue point (EVRP) were investigated to evaluate airflow patterns and pressure interactions under train-induced flow conditions.

In addition, meteorological pressure differences between the tunnel portals were recorded and analysed to quantify their influence on longitudinal airflow and pressure balance within the tunnel system. The results provide valuable experimental data for validating numerical models, supporting commissioning activities, and improving the design and operation of future long railway tunnels subjected to high-speed traffic.

Keywords: High-speed railway tunnels; Tunnel aerodynamics; Pressure loads; Dust exposure; Commissioning measurements

1. INTRODUCTION

Long railway tunnels designed for high-speed traffic represent highly complex aerodynamic systems in which train-induced flows, ventilation concepts, structural constraints, and operational safety requirements interact under transient conditions. While numerical simulations provide essential tools for design and planning, full-scale measurements under real operating conditions remain rare. Such measurements are, however, indispensable for validating design assumptions, improving model accuracy, and understanding coupled physical phenomena that cannot be fully captured by theoretical approaches alone.

The commissioning phase of the Koralm Tunnel offered a unique opportunity to use the tunnel as a real-world laboratory. During this phase, the mechanical equipment was already installed and high-speed train movements could be performed under controlled conditions, enabling comprehensive experimental investigations within a fully functional tunnel environment. This setting allowed the observation of aerodynamic, operational, and safety-relevant effects at full scale and under realistic boundary conditions, which are typically inaccessible once regular rail operation begins.

Within this framework, a series of coordinated measurement campaigns was carried out to address key questions related to occupational safety, aerodynamic behaviour, ventilation performance, and the interaction between train movement and tunnel infrastructure. The investigations focused not only on phenomena within the tunnel but also on their impact on adjacent technical rooms, emergency ventilation systems, and the overall pressure balance of the tunnel.

The data obtained from these experiments serve multiple purposes. They support the validation of numerical models used in tunnel design, contribute to the optimisation of ventilation and safety concepts, and provide practical insights for the commissioning of technical equipment. Furthermore, the findings offer valuable reference data for future long railway tunnel projects exposed to high-speed traffic, where comparable full-scale experimental evidence is typically unavailable.

2. KORALM BAHN, KORALM TUNNEL

The so called ‘Southern Corridor’, which includes the Koralm railway (*Koralm Bahn*, KAB), is part of the about 4’600 km long Baltic Sea –Adriatic Sea Corridor (BSAS) of the Trans European Transport Network (TEN–T). It represents the eastern transalpine north-south link and connects the ports and regions in the north (Baltic Sea, Baltic region, Poland) with Central Europe and the ports and regions in the upper Adriatic area.

The KAB, with a length of about 130 km, connects the Austrian federal regions Styria and Carinthia, and their capital cities Graz and Klagenfurt. The key element of this new route is the Koralm Tunnel (KAT) with a length of 32.9 km and a maximum rock overlying of about 1’200 m. The two single-track rail tunnels are connected via cross-passages every 500 m. These serve as escape routes and also contain the necessary equipment for tunnel operation. An underground Evacuation and Rescue Point (EVRP), approximately 1 km in length, is located between the two tubes near the center of the tunnel.

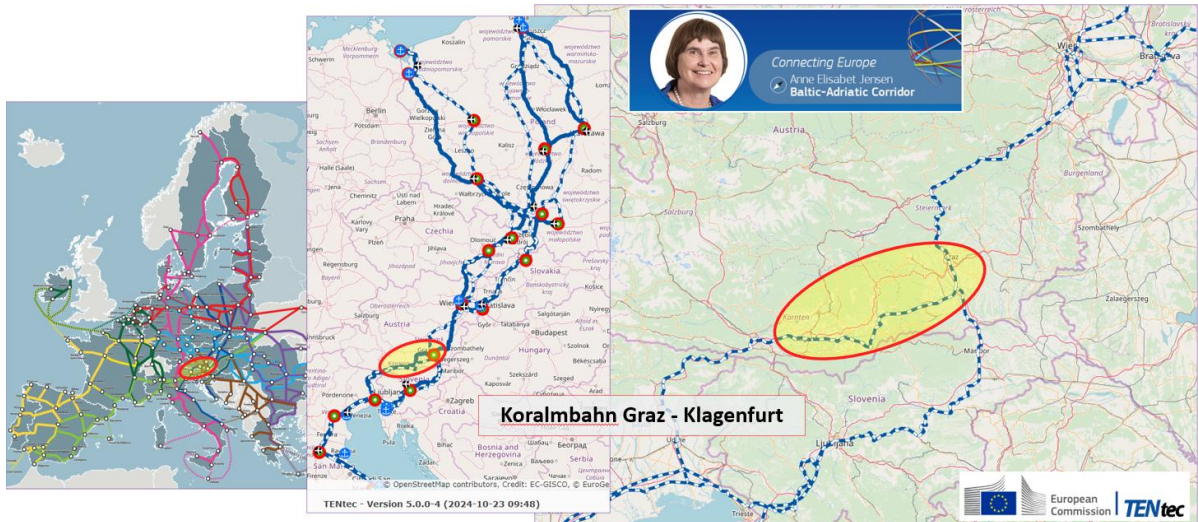


Figure 1: Baltic Sea -Adriatic Sea Transport Corridor [EU / ÖBB]

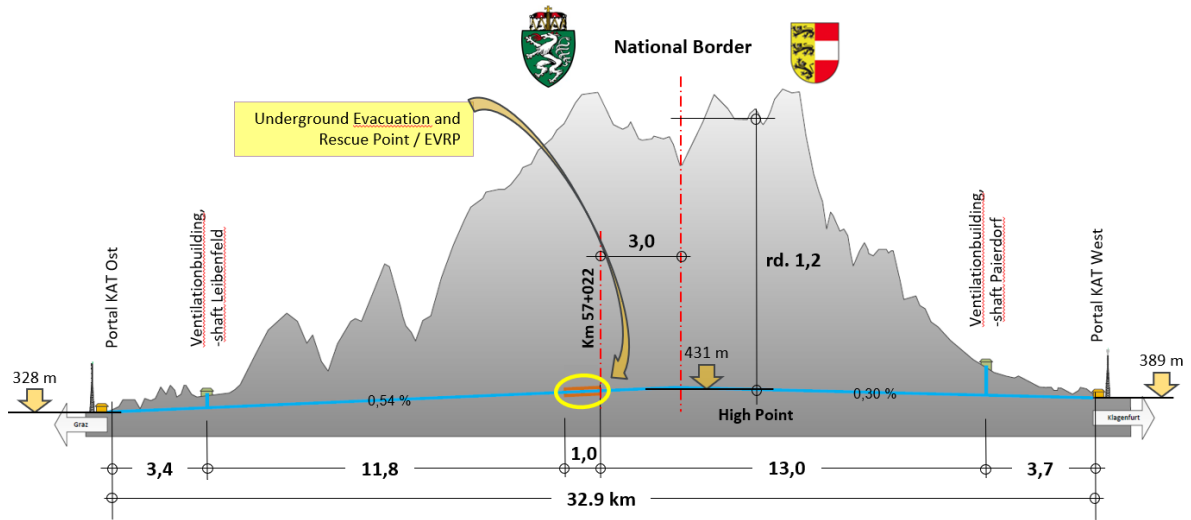


Figure 2: Koralm Tunnel - overview longitudinal section [ÖBB]

3. SURFACE ROUGHNESS

In the aerodynamic design of ventilation systems for railway tunnels, values taken from literature are commonly used to estimate the surface or friction coefficient [1] [2] [3]. This approach is based on the relationship between the Reynolds number and the friction coefficient, as flow losses are strongly influenced by the flow regime and the condition of the tunnel wall. In railway tunnels, the Reynolds number, depending on tunnel cross-section and flow velocity, typically ranges from approximately 4.5×10^5 to 1.5×10^8 [1], [2]. Under these conditions, the flow is always fully turbulent, and wall roughness has a major influence on the friction coefficient.

For an exact determination of the friction coefficient, the average roughness height of the tunnel surface would be required. In practice, however, this information is usually not available. Therefore, empirical values from the literature are often applied. Depending on the quality of the concrete surface and the presence of installations, roughness coefficients are typically assumed to range from $\lambda=0.013$ to $\lambda=0.025$ [4]. A commonly used reference value for a tunnel tube with minor obstacles is approximately $\lambda=0.015$ [4].

During the commissioning phase of the Koralm Tunnel, dedicated measurements were carried out to experimentally determine the actual surface friction coefficient. Over a measurement length of 500 m, the loss of pressure was recorded at a mean flow velocity of 6.2 m/s. To determine the air density, air temperature and air pressure were measured during the test using a Testo 400 device. The loss of pressure was measured using a 500 m long plastic tube connected to a high-precision differential pressure sensor manufactured by Halstrup-Walcher (measurement range 250 Pa \pm 0,5% FS). The flow velocity was determined contact-free using an ultrasonic flow measurement device, which measures velocity along a defined measurement path (measurement accuracy \pm 0.2 m/s). In the measurement section, the tunnel is constructed using segmental lining in the form of precast concrete segments (see **Figure 3**).



Figure 3: Finish of the tunnel surface

Using this measurement setup, an average tunnel friction coefficient of $\lambda=0.0158$ was determined. This value includes not only the concrete tunnel surface but also typical tunnel installations such as the fixed catenary, handrails, and leaky feeder communication cable, small signs (20 cm \times 20 cm), thus providing a realistic parameter for aerodynamic design.

4. METEOROLOGICAL PORTAL PRESSURE DIFFERENCE

Another key parameter in the design of ventilation systems for long railway tunnels is the consideration of meteorological influences. Especially in tunnels with significant overburden, very different weather systems can prevail simultaneously at the two portals. These differences can lead to considerable portal pressure differences, which strongly influence the longitudinal airflow within the tunnel. Pure wind effects are of secondary importance in such cases, as the resulting wind pressures can be up to one order of magnitude smaller than the portal pressure differences.

For a reliable determination of these portal pressure differences, highly accurate absolute pressure sensors are required. The measurement accuracy should be in the range of approximately \pm 5 Pa. Conventional meteorological absolute pressure sensors, however, often provide accuracies of only about \pm 50 Pa and are therefore of limited suitability for this purpose.

During the planning phase, site-specific measurement data are often not available. In practice, data from nearby meteorological stations are therefore commonly used. In addition, it must be defined in advance which percentile of the measured portal pressure differences is relevant for the dimensioning of the ventilation system. In Austria, for example, the 95th and 98th percentiles of hourly mean values are frequently applied for road tunnels [5].

In the design of the ventilation system for the Koralm Tunnel, absolute pressure, air temperature, and relative humidity were taken into account. For this purpose, five-year time series from meteorological stations operated by Geosphere Austria located near the tunnel portals were used (approximately 3 km in straight-line distance from the eastern portal and about 4.5 km from the western portal). Based on the measured absolute pressures, portal pressure differences were calculated, taking into account the respective installation heights of the sensors, and the 95th percentile relevant for ventilation design was derived.

Since these stations are not located directly at the tunnel portals, and since the absolute pressure sensors used have limited measurement accuracy, a one-year direct measurement campaign of the absolute pressures was conducted at the portals from October 2024 to October 2025. These measurements with highly accurate absolute pressure sensors were subsequently compared with the data from the meteorological stations of Geosphere Austria in order to assess and validate the reliability of the previously used data basis and to evaluate the differences between the two measurement methods.

Table 1: Percentile comparison between directly measured portal differential pressure using high-precision absolute pressure sensors (left) and meteorological measurements from further away using standard absolute pressure sensors (right).

portal differential pressure measurement			meteorological measurement		
percentile	pressure on the east portal	pressure on the west portal	percentile	pressure on the east portal	pressure on the west portal
	[Pa]	[Pa]		[Pa]	[Pa]
100	331	518	100	356	531
95	112	220	95	131	192
90	86	168	90	106	136
85	65	135	85	89	103
80	50	113	80	73	81
50	0	28	50	2	0

The one-year absolute pressure measurements carried out directly at the portals using high-precision sensors clearly show that the assumptions made for the ventilation design are adequate. In comparison, the data from more distant meteorological stations equipped with standard absolute pressure sensors exhibit significant deviations. In some cases, the actual portal pressure differences are considerably overestimated, while in others they are underestimated.

However, these parameters are essential for the safe and energy-efficient operation of the ventilation system. It is therefore recommended to conduct meteorological measurements with high-accuracy absolute pressure sensors in the immediate vicinity of the tunnel portals as early as possible, ideally before the planning phase begins.

5. DUST GENERATION

A particularly interesting aspect is dust exposure during the commissioning phase. At this time, there is still a lot of work left to be done in the tunnel. At the same time, so-called stepwise high-speed test movements are frequently conducted. These movements generate strong air movements that can resuspend dust and thereby significantly increase PM concentrations. The limit values relevant to workplaces are particularly interesting in this context. ([6], [7], [8]):

Substance	Limit type	Value	Unit
Fine quartz (<2.5µm)	8 hours	0.1	mg/m ³

Several studies on dust exposure in railway tunnels already exist (e.g. [9] [10] [11]). However, their primary objective was to determine emissions from rail traffic. These studies do not provide information on 8 hours workplace concentrations.

Air quality during the commissioning phase is of special interest, as completion works inside the tunnel are conducted at this time. At the same time, so-called stepwise high-speed test movements are often conducted during this phase. These train activities generate a strong air flow, which leads to resuspension of dust and thereby higher PM levels. A few studies about PM exposure in railway tunnels and emission from railways have been conducted. These mainly refer to tunnels that have been in operation for many years. Stepwise high-speed test movements are an essential part of the commissioning process of railway tunnels, particularly on high-speed lines. Their purpose is to verify the interaction between the train, the fixed catenary or conductor rail, the tunnel geometry, and the aerodynamic boundary conditions under real operating conditions. Stepwise high-speed test movements refer to the gradual increase of train speed up to the intended operating speed, with measurements and observations carried out at each speed level.

To investigate PM levels in the Koralm Tunnel, dust measurements were carried out over a period of one month in a tunnel section located approximately 6 km from the western portal. A particle analyser was used to record the particle mass concentration and particle size distribution with high temporal resolution. The instrument operates based on the light-scattering principle, in which particles are assigned to defined size classes. An internal algorithm is then used to calculate particle volume and particle mass. For this purpose, the analyser applies a particle density corresponding to a typical environmental aerosol. Since the actual particle density of the tunnel aerosol during the commissioning phase is still strongly influenced by construction activities and, in addition, emissions from passing trains contain a higher proportion of heavy metals, the default particle density needs to be corrected. For this reason, a cascade impactor was employed, which allowed for parallel sampling of PM₁₀, PM_{2.5}, and PM₁ fractions on filters. By weighing the filter samples before and after the tests, the actual particle mass of aforementioned PM fractions could be determined and a correction factor for the online measurement could be derived.

Figure 4 and **Figure 5** illustrate the PM levels (1-minute average values) during a single train pass at the beginning of the measurement period. From these measurements, an 8-hour average value was subsequently calculated in order to allow comparison with the corresponding limit value. In addition, one measurement day with several trains passing in short intervals was evaluated, and the 8-hour average was also determined for this case. **Figure 4** shows the results of the dust measurement on 7 May 2025. A Railjet passed through the tunnel at 250 km/h. No further train movements were scheduled for the rest of the day. During this movement, PM₁₀ concentrations of approximately 9,730 µg/m³ were recorded. The PM_{2.5} peak-concentrations reached 1,450 µg/m³, and the maximum PM₁ was 240 µg/m³. It took roughly 5 hours to again reach the background concentrations. In contrast, **Figure 5** shows the dust measurement from 12 May 2025. The Railjet travelled through the tunnel at only about 50 km/h. Again, no further train movements took place for the remaining day. Slightly higher PM₁₀ peak values were measured than during the 250 km/h movement, with a maximum of approximately 9,980 µg/m³. PM_{2.5} concentrations ranged between 4 and 1,360 µg/m³, and PM₁ values between 3 and 201 µg/m³. Background levels were reached after approximately 3.5 hours.

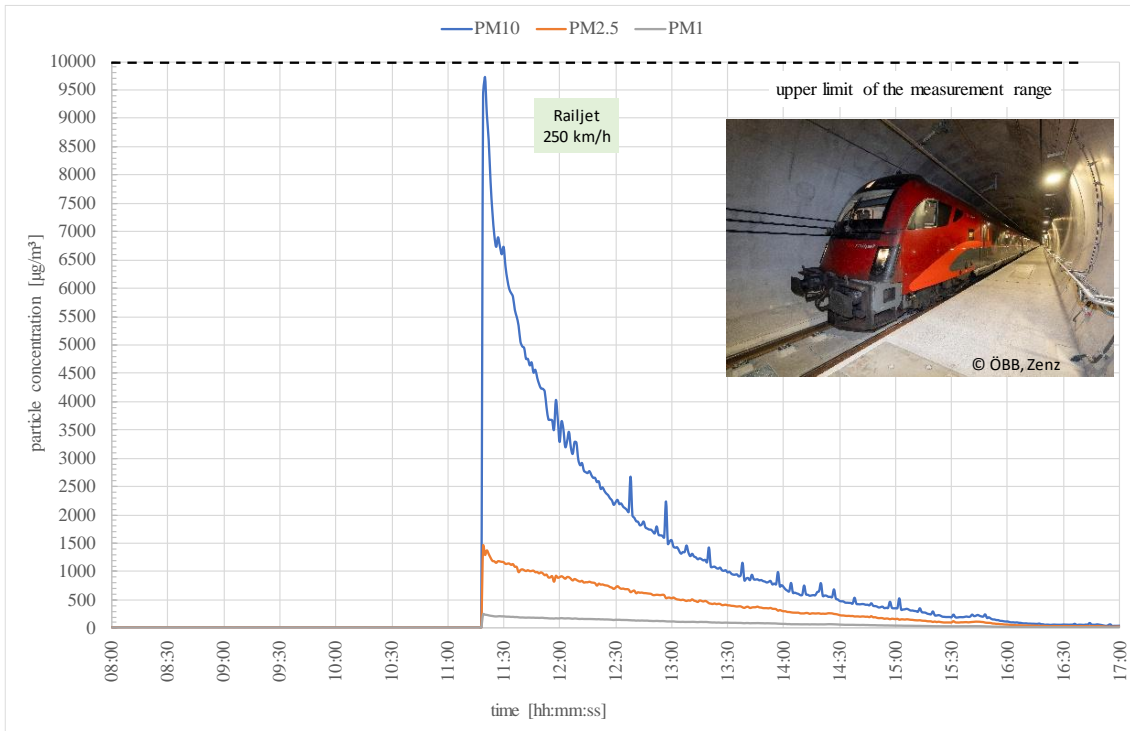


Figure 4: PM1, PM2,5 and PM10 concentration on 07.05.2025 – Railjet v=250km/h

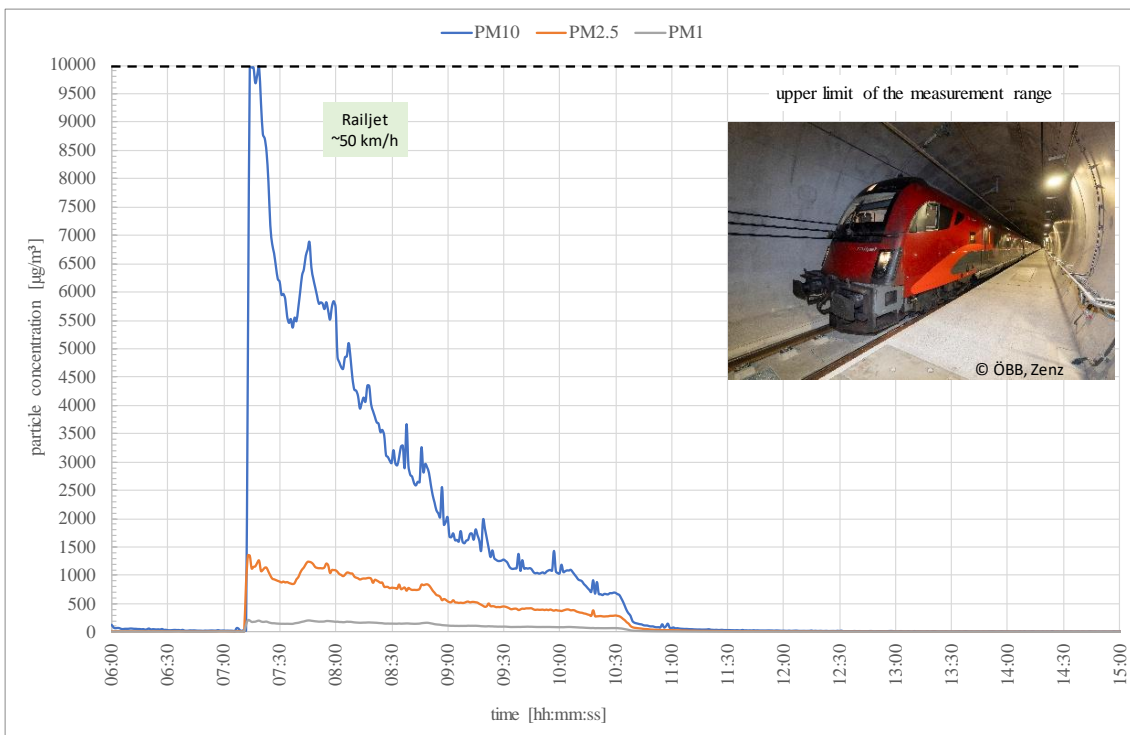


Figure 5: PM1, PM2,5 and PM10 concentration on 12.05.2025 – Railjet v~50km/h

For a final comparison, a measurement day at the end of the campaign was selected, during which six trains passed the test location. The train movements were scheduled in intervals of roughly one and a half hours. The train speed varied between 160 km/h and 230 km/h. **Figure 6** shows the results of the dust measurement on 10 June 2025. The Railjet passed through the tunnel in short time intervals at speeds of 160 km/h, 180 km/h, 200 km/h, and 230 km/h. The peak PM concentrations were 8,085 $\mu\text{g}/\text{m}^3$ (PM10), 1,110 $\mu\text{g}/\text{m}^3$ (PM2.5) and 201 $\mu\text{g}/\text{m}^3$ (PM1). After the last train pass, background levels were reached again after five hours.

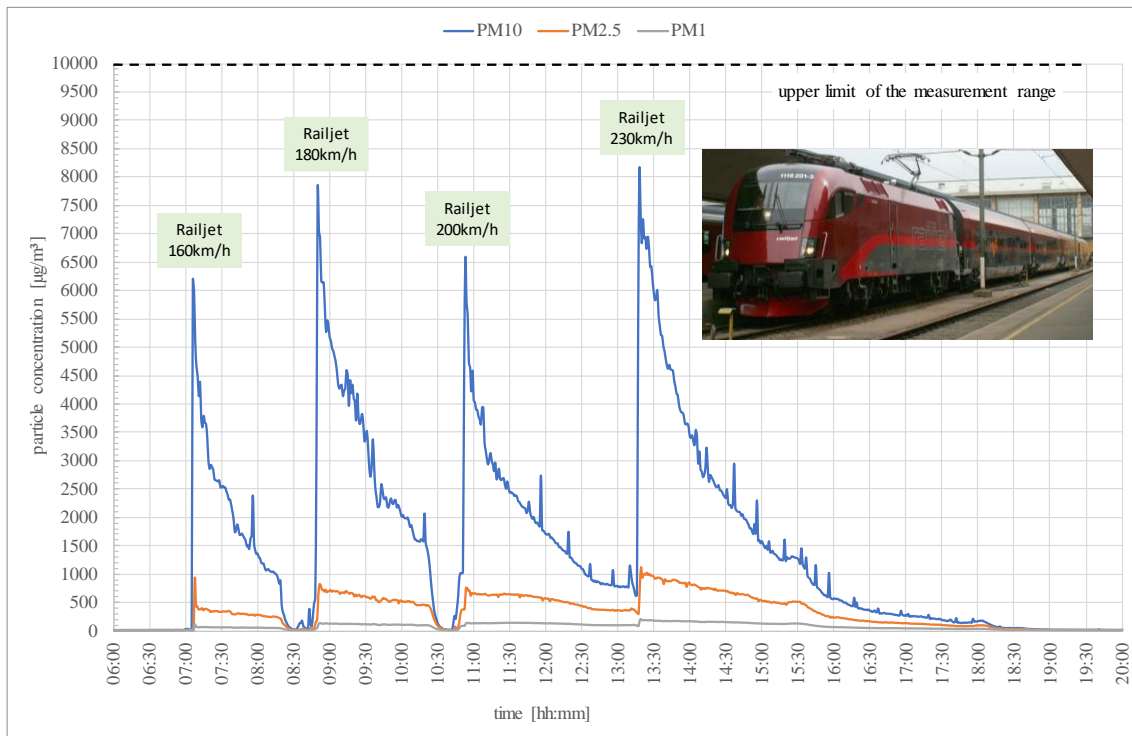


Figure 6: PM1, PM2,5 and PM10 concentration on 10.06.2025 – Railjet v=160km/h, v=180km/h, v=200km/h, v=230km/h

To assess dust exposure with respect to the 8-hour limit value, the corresponding time-weighted averages for PM10 were calculated for the three measurement days presented and compared with the respective limit value. To calculate the average value for the 8-hour period, the calculation was started immediately when the maximum peak began to rise.

measurement day	Limit type	Value	Unit
07.05.2025	8 hours	0.28	mg/m ³
12.05.2025	8 hours	0,30	mg/m ³
10.06.2025	8 hours	0.50	mg/m ³

Based on the results of the dust investigation, it can be concluded that appropriate protective measures must be provided for persons present in the tunnel during train operations in the commissioning phase (e.g., wearing FFP3 respiratory masks, reducing the duration of stay, etc.). However, access to the railway tunnel is usually not permitted while trains are running. Assuming that work can only be carried out several hours after the trains have passed, the dust problem is mitigated accordingly.

6. FILTER SERVICE LIFE

The Koralm Tunnel has a total of 69 technical cross passages, arranged at intervals of 500 m. These cross passages contain the technical equipment required for tunnel operation, organized into five different room categories like the telecommunication room. The telecommunication room is particularly critical, as a maximum room temperature of 22 °C must be maintained there. To ensure this temperature, cooling of the telecommunication room is necessary. On the one hand this is due to the high rock temperature, which ranges from about 16 °C near the portals to approximately 31 °C in the sections with the highest rock coverage, and, on the other hand, to the considerable heat dissipation from the electronic components required for safe tunnel operation. In the central sections of the tunnel with large coverage and correspondingly high rock temperatures, the telecommunication rooms are therefore cooled

using standard air-conditioning systems. In cooler sections of the tunnel (a total of 29 cross passages), the telecommunication rooms are cooled using air taken from cooler one of the two tunnel tubes. The tunnel air is filtered and used to cool the electronic equipment. The warmed air is then discharged back into the tunnel. To ensure the required cooling performance, the airflow rate must be at least 1.1 m³/s. Air filtration is done through a coarse (ISO 16890, Coarse 90%) and a fine dust (ISO 16890, ePM10 80%) filter

The coarse and fine dust filters are the main components influencing the airflow rate of the cooling fans. As dust loading of the filters increases, the overall system resistance rises and the operating point of the fan shifts. The maximum acceptable total pressure loss for coarse and fine dust filters should not exceed 470 Pa. The permissible change in flow rate within the system, together with the fan operating point, the fan characteristic curve, and the total system pressure, determine the allowable increase in resistance of the two filters.

For planning service intervals of the coarse and fine dust filters, it was necessary to determine reference values for filter service life. For this purpose, in-situ investigations were initiated. The objective was to record and analyse the temporal behaviour of dust loading on a specific coarse and fine dust filter during continuous operation with high train frequency. The collected data were used to support statements about the accumulation patterns of dust on the filters and to estimate the approximate filter service life. The configuration of the test setup essentially corresponded to the air-cooling system used in the Koralm Tunnel (see **Figure 7**).

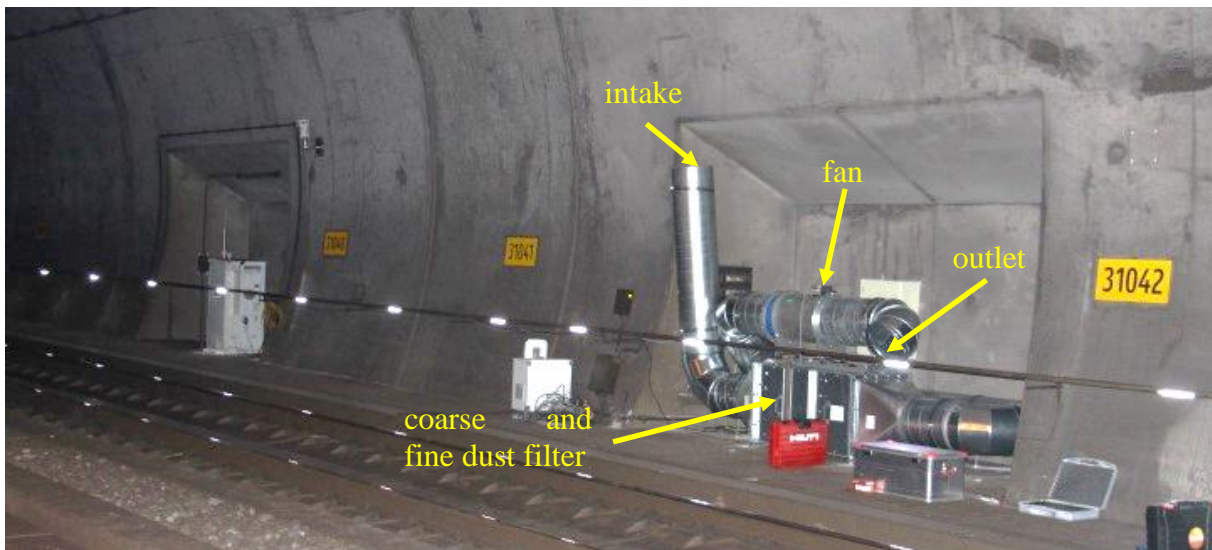


Figure 7: Test setup in tunnel Münster [12]

About the measurement period, the airflow rate of the fan decreased from an initial value of about 1.6 m³/s to approximately 0.9 m³/s. The critical point, defined as the airflow dropping below 1.1 m³/s (minimum volume flow for cooling), was reached approximately 42 days after the start of the measurement. At this time, the pressure loss of the coarse dust filter was about 140 Pa, the pressure loss of the fine dust filter was about 206 Pa, and the total pressure loss approximately 350 Pa. The results of the test are shown in **Figure 8**.

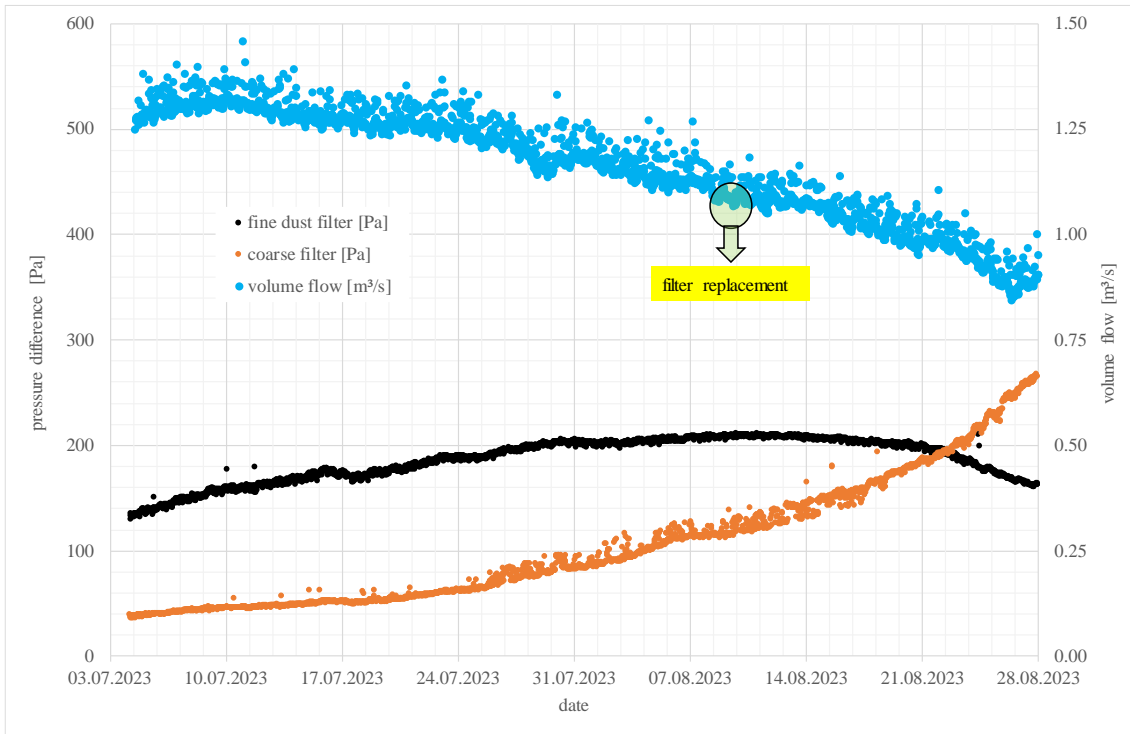


Figure 8: Temporal development of filter pressure losses and airflow rate.

During the test period, the average measured daily PM10 concentration was about $53 \mu\text{g}/\text{m}^3$ (daily mean value), with values ranging between $80 \mu\text{g}/\text{m}^3$ and $360 \mu\text{g}/\text{m}^3$.

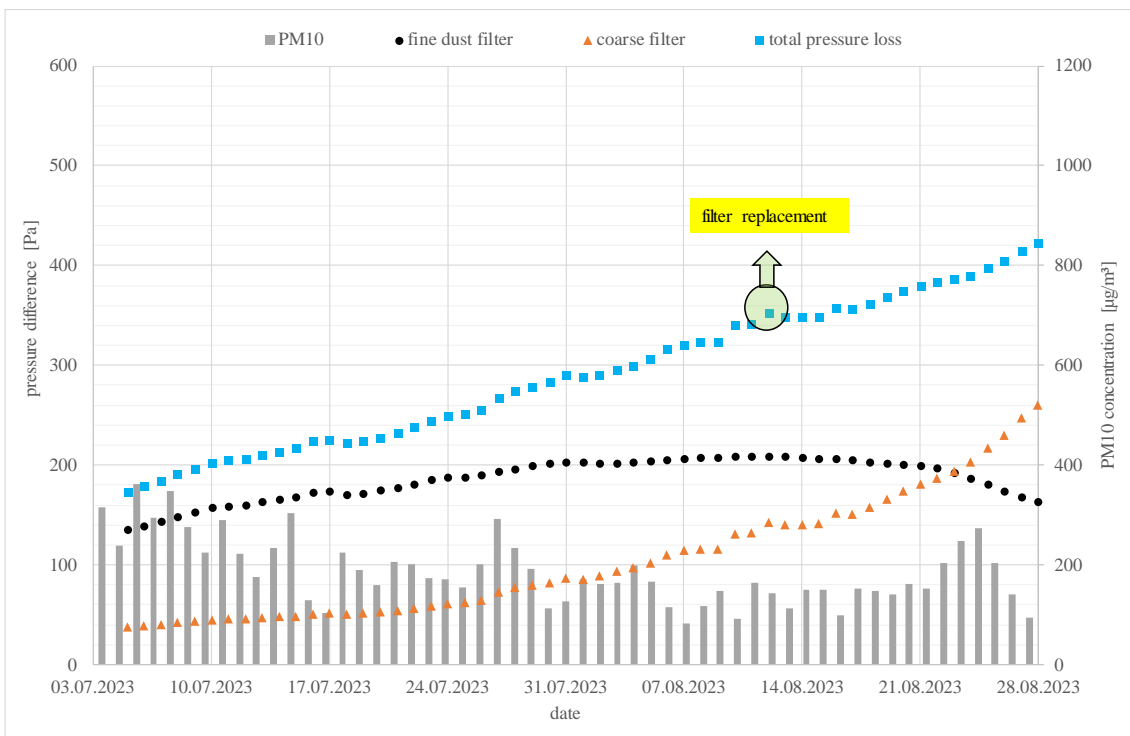


Figure 9: Temporal development (daily average values) of the pressure losses across the coarse and fine dust filters and the PM10 concentration in the tunnel air – operation at 50 Hz.

7. PRESSURE LOADS CAUSED BY TRAIN PASSAGES

Train-induced dynamic pressure loads generated by entering or passing trains in railway tunnels represent a significant aerodynamic stress on tunnel structures and their technical installations. Particularly in long tunnel structures, these transient pressure loads can lead to complex pressure profiles that affect both the main tunnel cross-section and connected structures such as cross passages, technical rooms, and ventilation structures. As part of a detailed measurement campaign, dynamic pressure loads were recorded in the KAT in both tunnel tubes, in front of cross passages CP56 and CP63, as well as within the cross passages. The objective of the measurement campaign was to systematically record and quantify the pressure loads occurring during the stepwise high-speed test movements in the tunnel itself and their propagation into the corridor of the CP, the telecommunications room (TC) and into the low-voltage (LV). Ultra-stable piezoresistive miniature absolute pressure sensors were used for the pressure measurements. This calibrated and temperature-compensated sensors provided highly accurate and stable absolute pressure readings over a wide temperature range. The characteristic parameters of the pressure sensor are listed below.

Measuring range	0 to 15 psi
Compensated temperature range	-20 °C to +85 °C
Operating temperature range	-40 °C to +125 °C

Figure 10 shows the locations and labelling of the monitoring points for CP56 and in both tunnel tubes. In both tunnel tubes, two pressure sensors were installed directly in front of the cross passage. One absolute pressure sensor was mounted on the inner lining of the tunnel (MP24/25), and the second on the wall panel on the side facing the tunnel (MP13/16). These two monitoring points allowed for recording the initial pressure signature of the passing train. To capture the propagation of the pressure waves into the telecommunication room and into the escape route, five additional pressure sensors were installed in the telecommunication room (MP43), the adjacent the low-voltage (MP49) room and the escape route (MP12/35/45).

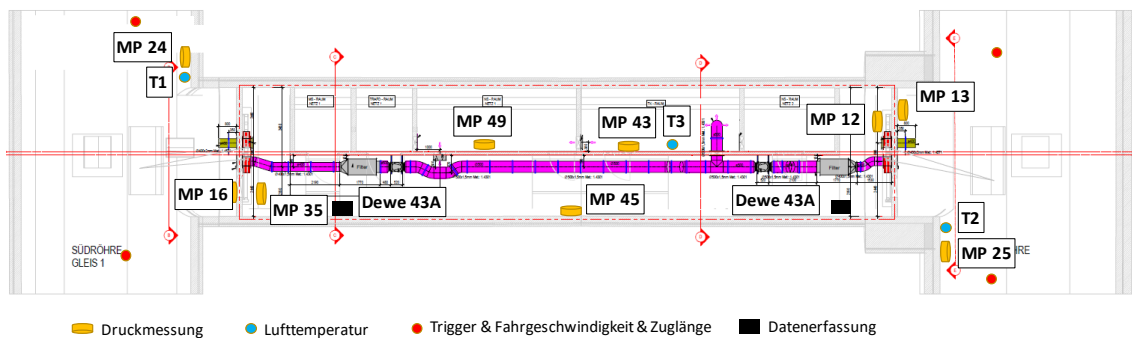


Figure 10: Measurement setup CP56

During the measurement campaign, a wide variety of trains passed through the Koralmtunnel. However, detailed information regarding train type and train length was not available. An evaluation of the train speeds shows that most train movements occurred at approximately 160 km/h. These movements fall within the speed class of 150 km/h to 175 km/h. **Figure 11** provides an overview of the defined speed classes.

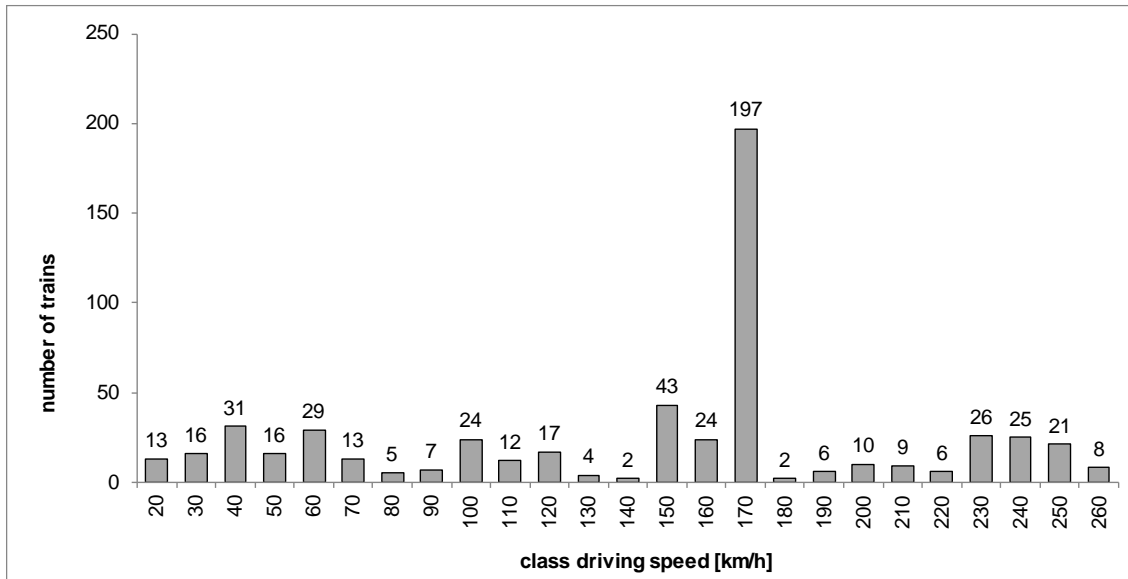


Figure 11: Train speed classification.

Figure 12 presents a summary of all measured maximum pressure loads (over- and underpressure) in the two tunnels, independent of the direction of movement. The figure also includes mathematical functions for the different monitoring points and pressure load ranges. A separate evaluation is required because the measuring points are located in cross-sections with different clear cross-sectional areas (CP56 track 1 = 42,66 m², CP56 track 2 = 51,2 m² and CP63 track 1 = 51,26 m², CP63 track 2 = 48,58 m²). Dynamic pressure generally increases quadratically with train speed. Applying this relationship to the pressure loads induced by pressure waves shows very good agreement with the measurement data. At the same time, it becomes evident that the measured values exhibit considerable scatter, which is likely related to the aerodynamic shape and length of the rolling stock, as well as the direction of movement (distance between the portals and the respective measuring point).

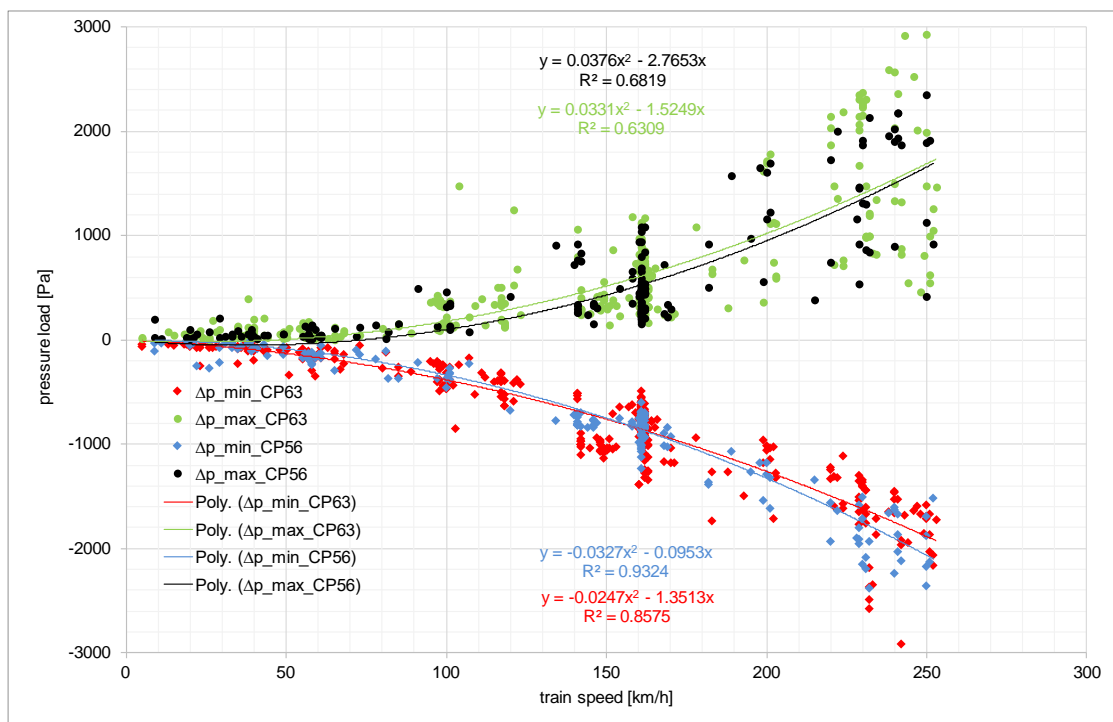


Figure 12: Pressure load based on all train movements at measuring points CP56 and CP63 in both tunnels.

8. SUMMARY

In particular, the commissioning test runs at the KAT were deliberately used to conduct in-situ experimental programs addressing a variety of research questions. Within the framework of these investigations, valuable practical experience was gained and relevant measurement results were obtained. The insights derived from these studies can be applied to future projects involving high-speed and long railway tunnels. The long-term objective is to further optimize the environmentally friendly and highly efficient railway system and to support its successful and innovative development in the future.

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