 DOI: 10.3217/978-3-85125-883-7-27

DETERMINATION OF AERODYNAMIC LOADS IN RAIL TUNNELS USING MEASUREMENTS

Rodler J.[1], Huber A.[2]
[1]FVT mbH, Austria
[2]GRUNER GmbH Ingenieure und Planer, Austria

ABSTRACT

When a train passes through a tunnel, pressure variations are generated which propagate along the tunnel at sonic speed and are reflected back at portals into the tunnel. These pressure variations may cause aural discomfort or, in the worst case, aural damage to train passengers and train staff and will produce transient loads on the structure of trains and the infrastructure components. [4]

To define a clear interface between the subsystems of rolling stock and infrastructure, the train-induced aerodynamic pressure variations inside tunnels need to be known and limited. In order to specify and to limit the train-induced aerodynamic pressure variations inside tunnels, reference cases for rolling stock assessment are defined. [4]

The increase of the speed limit up to more than 200 km/h for trains of VR Group (Finland) on coastal line (between Helsinki and Turku) in the unrestricted mixed rail-traffic operation required analyses and measurements regarding possible pressure loads. In this process, the relevant aerodynamic properties of the rolling stock are determined based on full-scale tests and compared with the directives of TSI and national directives.

This paper describes the test procedure with sophisticated in-house developed pressure measurement device. The difficulties of pressure measurement using differential pressure sensors especially for this application is pointed out and a new solution is shown.

Keywords: TSI, aerodynamic loads, rail tunnel, train-tunnel pressure signature, pressure measurements

1. INTRODUCTION

When a train passes through a tunnel, pressure waves at sonic speed are propagated in the tunnel. The compression wave (frontal wave) generated currently the train enters the tunnel is reflected at the opposite portal as an expansion wave. Just when the train tail enters the tunnel, an expansion wave (rear wave) is generated and reflected at the portal as compression wave. Due to unfavourable superposition of waves the pressure amplitude increases, which effects high loads on tunnel equipment and built in components.

However, a small part of the compression wave exit the tunnel and radiates outside, in the form of an impulse-like micro-pressure wave. This can create a booming noise and causes noise pollution in a wide area around the tunnel exit.

Furthermore, pressure variations affects aural pressure comfort for passengers and staff in trains and in worst case, they can cause permanent health damages.

Pressure variations are described by means of the gauge pressure, p(t), measured in time and referenced to atmospheric pressure. The external pressure, p_e, usually denotes the pressure outside a train, or equally inside a tunnel. The internal pressure, p_i, usually denotes the pressure inside the train or generally in any enclosed air volume that is present in the tunnel system. The internal pressure responds to the external pressure and is dependent on the pressure sealing of the train or generally any structure that separates its internal volume from the external environment. In order to assess the effects at the surface between the external and internal environments, the pressure difference p_d is determined. This pressure difference is one source of structure loading. [4]

With regard to aerodynamics, a train have to fulfil the required characteristic pressure changes for a given combination (reference case) of train speed and tunnel cross-section. The assumption is that a single train passes through a standard, straight tubular tunnel (without shafts etc.). Since full-scale measuring of every combination is not possible, calculation results with validated simulation models are accepted. The model building and validation bases on measured pressure curves. The possible procedure of measuring the pressure curve is described below.

2. IMPORTANT GUIDELINES

2.1. Technical specifications for the interoperability (TSI)

The European Commission has passed technical specifications for the interoperability (TSI) in the trans-European high-speed railway system and in the conventional trans-European railway system and has published them in the respective gazettes of the European communities.

The technical specification for interoperability (TSI) relating to the ‘rolling stock — locomotives and passengers rolling stock’ subsystem of the rail system in the entire European Union, can be found in Commission Regulation (EU) No 1302/2014 of 18 November 2014. [2]

2.2. EN 14067-5

The EN 14067-5 document establishes aerodynamic requirements, test procedures, assessment methods and acceptance criteria for operating rolling stock in tunnels. Aerodynamic pressure variations, loads, micro pressure wave generation and further aerodynamic aspects to be expected in tunnel operation are addressed in this document. Requirements for the aerodynamic design of rolling stock and tunnels of the heavy rail system are provided. [4]

3. AERODYNAMIC CRITERION / TRAIN-TUNNEL PRESSURE SIGNATURE

The train-tunnel pressure signature can determine the aerodynamic properties of a running train in a rail tunnel. Figure 1 schematically shows the pressure variations generated when a train enters a tunnel.

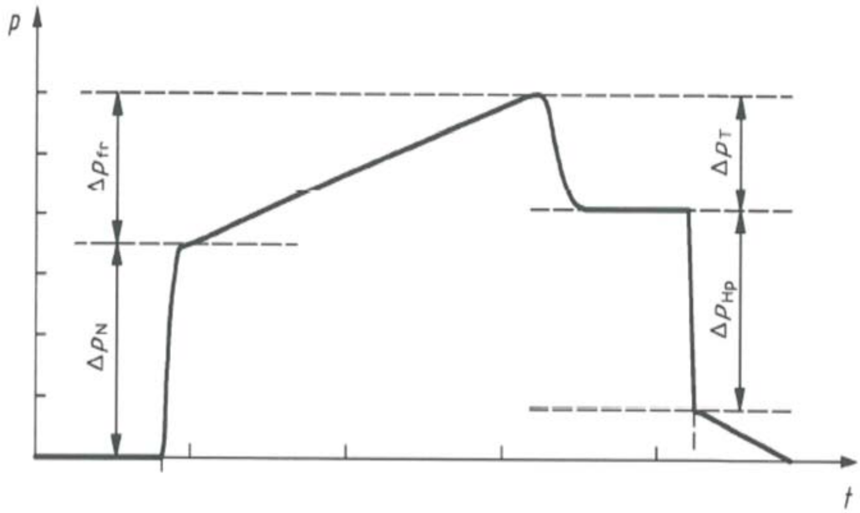

Figure 1: Train-tunnel pressure signature at a fixed place in the tunnel [4]

Δp_N Pressure rise generated by the frontal wave of the train nose entering the tunnel
Δp_{fr} Pressure rise generated during the tunnel passage due to the friction
Δp_T Pressure drop due to rear wave generated by train tail entering the tunnel
Δp_{Hp} Pressure drop during the passage of the train nose

The applicable characteristic limits for Δp_N, Δp_{fr} and Δp_T are compiled in Table 1.

Table 1: Maximum tunnel characteristic pressure changes for the reference case [4]

Maximum design speed km/h	**Reference case**		**Criteria for the reference case, Pa**		
	Reference speed, vtr,ref km/h	A_{tu} [m²]	Δp_N [Pa]	$\Delta p_N + \Delta p_{Fr}$ [Pa]	$\Delta p_N + \Delta p_{Fr} + \Delta p_T$ [Pa]
$v_{tr,\,max} < 200$	No requirements				
$200 \leq v_{tr,\,max} \leq 230$	200	53,6	≤ 1750	≤ 3000	≤ 3700
$230 < v_{tr,\,max}$	250 or $v_{tr,\,max}$[a]	63,0	≤ 1600	≤ 3000	≤ 4100

[a]The lower value of $v_{tr,\,max}$ and 250 km/h shall be applied

Evidence must be provided based on full-scale tests, carried out with the reference speed or a higher speed in a tunnel with a cross-section as close as possible to the reference case. The transfer to the reference requirement can be done with verified simulation software calibrated with the performed measurements.

4. QUANTIFICATION OF PRESSURE VARIATIONS

The quantification of pressure variations can be done with full-scale measurements at a given position in the tunnel or alternative with pressure measurements on a moving train and subsequent calculation of the values Δp_N, Δp_{fr} and Δp_T.

4.1. Measurements in the tunnel

Ideally, the values Δp_N, Δp_{fr} and Δp_T are measured at a fixed position in the tunnel. In EN 14067-5 [4] the equation for the distance x_p between the entrance portal and the measurement position is given:

$$x_p = \frac{c * L_{tr}}{c - v_{tr}} + \Delta x_1 \qquad \text{Formula 1}$$

The extra length Δx_1 (approx. 100 m) ensures a clear time-related separation of the pressure variations over time. The installation of the measurement devices near to the portal is meant to avoid a deadening of the pressure wave.

Figure 3 shows the pressure signals recorded in a tunnel for a specific train. The train speed was measured within the range of 198.9 to 201.6 km/h. Therefore, all curves are quite similar. Two curves (measurement 4 and measurement 6) are remarkable different. At the time of both measurements, flow speed of about 4 m/s was measured in the tunnel before the train passed. The direction of the flow was in opposite to the driving direction of the train in the tunnel. This resulted in higher pressures. All the other measurements were performed with air speeds less than 1.2 m/s, which resulted in a very good match of the pressure curves.

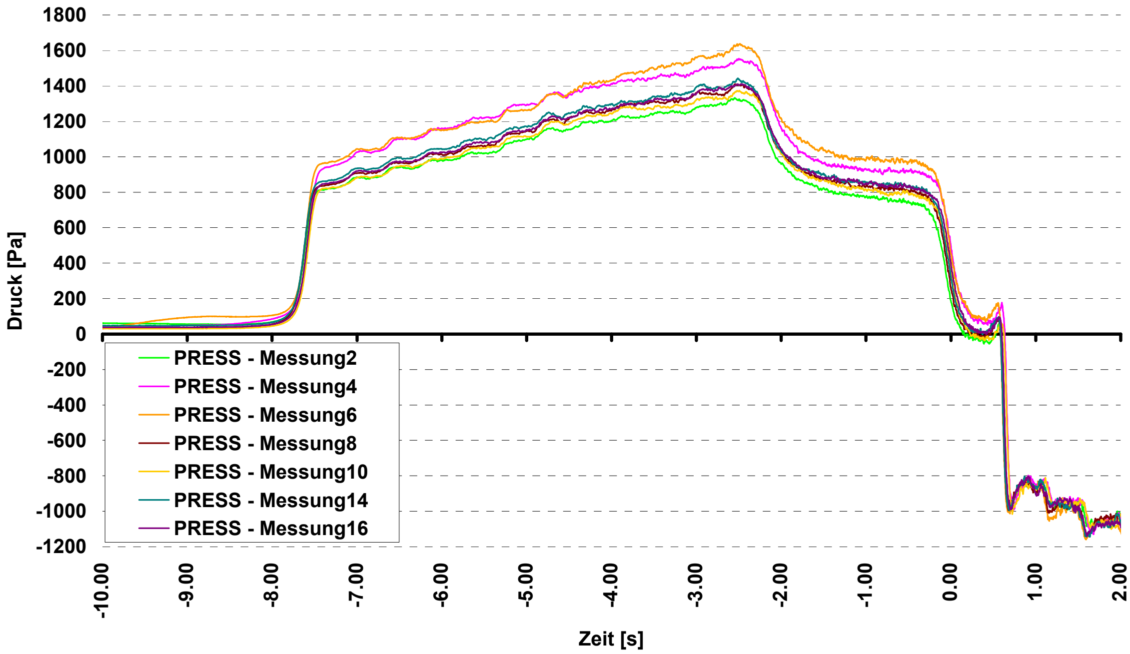

Figure 2: TSI pressure signal from a train measured on a fixed position in tunnel

4.2. Measurements on the train

Measurements on the exterior of the train are possible as well. Δp_N, Δp_{fr} and Δp_T can be approximated by measurements of $\Delta p_{N,o}$, $\Delta p_{fr,o}$ and $\Delta p_{T,o}$ (comp. Figure 3). If needed, Δp_{HP} can be derived either from predictive formulae or assumed to be equal to $\Delta p_{N,o}$.

The tunnel shall have a constant cross-sectional area, no side passages or airshafts and no residual pressures waves. Ideally, there should be no initial airflow in the tunnel. However, if there is, its influence on the measurements shall be checked.

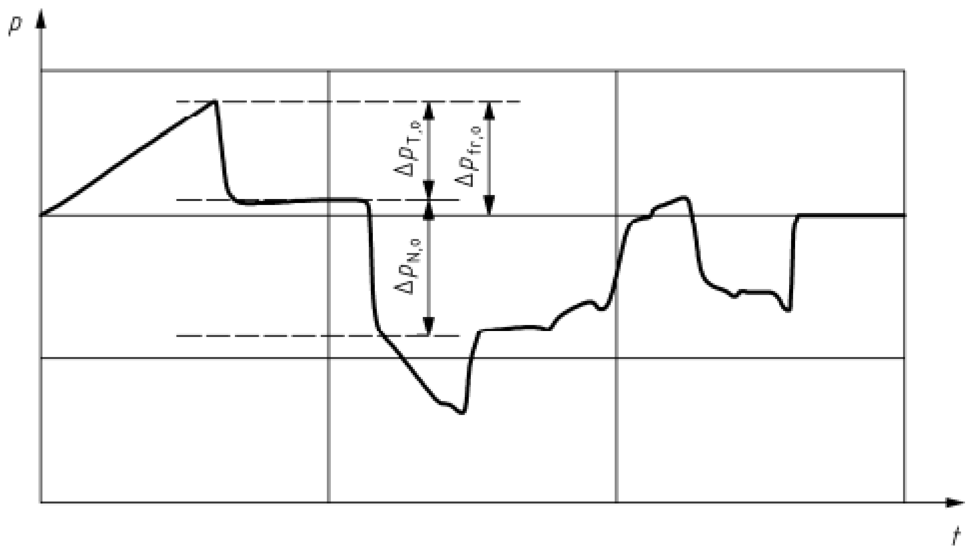

Figure 3: Train-tunnel-pressure signature on the nose of the train [4]

Pressures are measured using transducers on the exterior of the train. To get the complete frictional pressure rise, Δp_{fr}, it is necessary to measure the pressures on the outside of the train at a position just behind the nose at the position where the full cross-sectional area is reached. [4]

5. EXAMPLE FOR MEASUREMENTS ON A TRAIN

VR Group is a government-owned railway company in Finland. VR's most important function is the operation of Finland's passenger rail services. In 2019, the Finnish Transport Infrastructure Agency (FTIA) decided to increase train speeds on the coastal line. The coastal line located between Kirkkonummi and Turku is an approximately 162 km long railway track in the south of Finland. Along the track there are 15 single-bore, single-track tunnels with lengths from 43 m up to 1240 m.

The train speeds for each train (ICS, SM3) are limited by the track geometry. The actual speed for SM3 (Pendolino) on this route is 180 km/h to 200 km/h and is goingt to be increased to max. 220 km/h. The actual speed for ICS on this route is 140 km/h to 160 km/h and is going to be increased to max. 200 km/h.

Figure 4: SM3 (Pendolino) (left) (© Otto Karikoski) and ICS2 (right) (© Antti Leppänen)

5.1. Measurement Setup

Both test trains were equipped with several sensors outside and inside the train. The ideal sensor positions are right behind the nose, right before the rear and in the middle of the train. At the nose and at the rear the pressure maxima respectively minima along the train can be expected in long tunnels. The center position provides additional information about the pressure evolution along the train during tunnel passages, which might be useful especially in short tunnel.

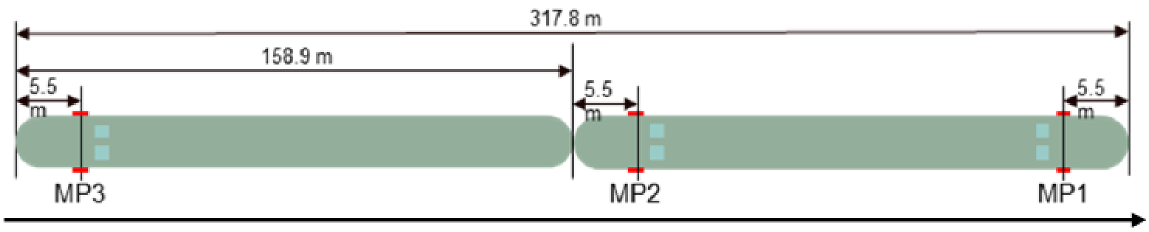

Figure 5: SM3, sensor position along the train [5]

Every measurement position (MP1 - MP3) per train consisted of four external sensors (two on both sides of the train in different heights) and two sensors inside the train. The use of four external sensors provides redundancy and information about possible perturbation of the signal due to train geometry and local non-static pressure effects that can be caused by tunnel geometry. The sensor heights were chosen with respect to train geometry to avoid unnecessary noise on the signals.

Two sensors in the interior are used for redundancy reasons, furthermore they validate each other. If they are placed in the same coach as the outside sensors, their detailed position has negligible influence on the sensor readings because pressure travels at the speed of sound inside the train.

5.2. Measurement Devices

The requirements to measurement technique with regard to measurement frequency and accuracy is given in [4].

The pressure transducers shall be calibrated within the expected pressure range, typically ±4 kPa. The combination of pressure sensors and probes used shall be capable of measuring the pressure with a minimum of 150 Hz resolution. The measurement error of the measurement chain comprising the pressure transducer and the data acquisition system shall be less or equal than 2% of the expected value for $\Delta p_N + \Delta p_{fr}$.

The measurement of static pressure shall be made in a way to ensure that airflow in the tunnel does not affect the measurement. A suitable realization of such an installation is to use a flat mounting board with pressure taps set in it. The mounting board shall be as thin as possible. An example is shown in Figure 6. [4]

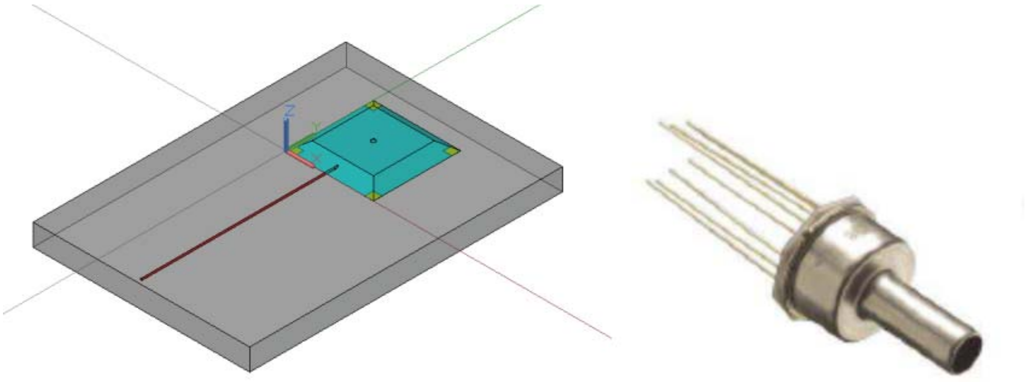

Figure 6: Mounting board with pressure tap (left) and the sensor used in the present case

In order to prevent a loss in (dynamic) information, the tubes and pipes between the pressure tap and the pressure transducer shall not exceed an overall length of 50 cm. The static pressure may be measured as a differential pressure relative to a common reference pressure (e.g. as stored in an insulated pressure reservoir). The structural flexibility and the volume of air in the tubes compared to the pressure reservoir shall be dimensioned to reduce this effect. A small leakage in the pressure reservoir may be necessary to adjust the reference pressure to slow ambient pressure changes. It shall be demonstrated that the leakage is not affecting the test during testing. [4]

Usual differential pressure sensors are used with reference volumes on their negative pressure input. However, experience has demonstrated that differential pressure measurement is not ideal because:

- Pressure changes in the tunnel act on the tubes connected to the pressure reservoir and may affect the reference pressure
- Reference volumes tend to extreme drifts caused by temperature change and poor tightness.
- Mechanical movement can lead to perturbation of the measured signals, which leads to major, not quantifiable inaccuracies of the measurement readings.
- Furthermore, the mounting of tubes along the train is not practicable within a suitable time span.

A new solution was developed and used for the present case using absolute pressure sensors. Naturally absolute pressure sensors are more inaccurate than differential pressure sensors due to their high measurement range therefor a precise ultra-stable high performance, temperature compensated piezo resistive silicon pressure sensor were used in each mounting board. Table 2 shows the characteristic parameters of the pressure transducer.

Table 2: Pressure sensor and barometer specification

Pressure sensor		**Barometer**	
Parameters	Value	Parameters	Value
Measurement range	0 to 15 psi	Measurement range	600 - 1100 hPa
Compensated temperature range	-20°C to +85°C	Temperature range	-25°C - +60°C
Working temperature	-40°C to +125°C	Accuracy	± 0.05 hPa
Non linearity	± 0.05% Span	Stability	< 100 ppm/year
Sample rate	500 Hz		
Response time	1 ms		

The pressure sensors are integrated in a mounting board (150 mm x 150 mm) to protect it against mechanical loads and weather effects. The pressure signal reaches the sensor via a perforation (1 mm diameter). The transfer properties of this system were taken into account in the installation of the measurement equipment.

The data recording was performed with a portable data logger (DEWE 43). This logger has eight analogue channels and multiple digital inputs and is able to captures measurement signals at scan rates up to 100 kSamples/s for each canal. The filtering and the averaging are done automatically inside the logger. The pressure signal were captured at a scan rate of 500 Hz.

Sensors shall be calibrated prior to use over the expected pressure range. This was done using a pressure vessel, which can be evacuated and pressurised. As reference, a calibrated very precise barometer was used (see specifications in Table 2).

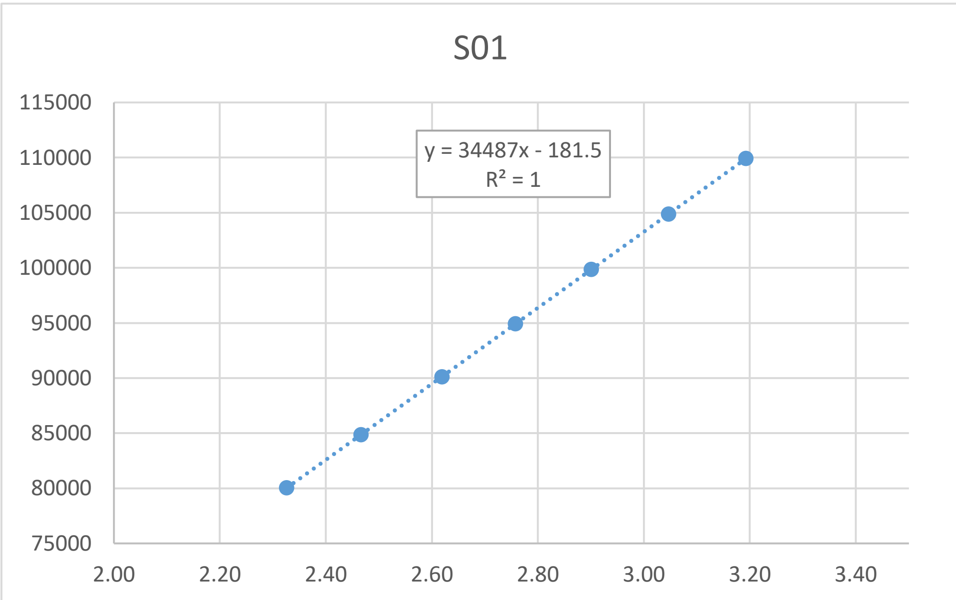

Figure 7: Calibration function for sensor S01 (sensor, amplifier, data acquisition)

6. RESULTS

Each tunnel passage was exported separately (150 passages x 3 measurement positions correspond to overall 450 passages).

All obtained signals were filtered with a 75 Hz zero phase shift low pass to reduce noise. Right before a tunnel passage, outside and inside pressure can be considered equal if the inside pressure had enough time to compensate (no tunnel exits right before the tunnel entry).

Based on this assumption, offsets were removed by subtracting the first value of each sensor from each of its samples. Figure 8 shows an example of the corrected data. The green line corresponds to the inside pressure. The four remaining lines correspond to the four outside pressures per measurement position. As expected, there are no major differences between the four measurement positions outside the train. During the full-scale test, pressure was measured during overall 150 tunnel passages on board of the SM3 and the ICS train.

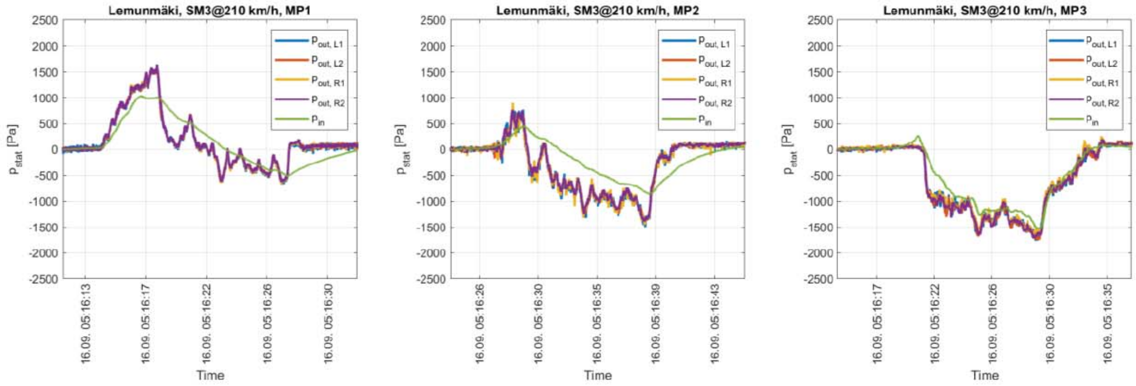

Figure 8: Outside and inside pressures at three measurement positions [5]

Each tunnel passage was visualized to identify invalid data like failure of the power supply, temporary failure of single sensors or data acquisition system, pressure-sealing malfunction, mistakes during export etc. Non-valid data were excluded from the results. Every data set was analyzed and documented concerning:

- maximum pressure outside the train,
- minimum pressure outside the train,
- TSI Health criterion,
- maximum positive pressure on the train wall (maximum of pin-pout),
- maximum negative pressure on the train wall (minimum of pin-pout),
- maximum pressure changes per second outside the train,
- maximum pressure change per second inside the train,
- comfort criterion within 1 second and
- comfort criterion within 4 seconds.

6.1. Simulation Program

The software ThermoTun was used for numerical simulation. ThermoTun is a computer programme accepted worldwide for the simulation of trains in tunnels and of tunnel systems. The correctness is confirmed by extended measurement campaigns (cf. [6]). With the programme, e.g. the following, aerodynamically relevant, unsteady values can be determined:

- Pressure variations of trains passing tunnels and on rolling stocks,
- Traction power requirements for trains in railway tunnels,
- Averaged air speed in the railway tunnel tube,
- Distribution and concentration of pollutants and smoke in railway tunnels.

The measurement results were recalculated with this software. Some parameters of the analysed train are varied as often as necessary until a good matching with the measurement was reached.

Subsequently, the pressure signatures could be calculated with the programme for the in TSI specified tunnel cross-section (A_{Tunnel} = 53.6 m^2).

7. CONCLUSION

A train must have aerodynamic properties that no damages occur for the train and for the tunnel installations when the train passes through a tunnel or passes by an oncoming train. Besides this, the comfort of the passengers must also be taken into consideration.

The increase of speed limit for trains on a specific railway section especially with tunnels requires full-scale measurements of pressure variations, because evidence must be produced about the aerodynamic properties of the train.

This paper describes the authorisation procedure to increase the train speeds on a specific route. It consists in full-scale measurements, which were done in Finland on the coastal line located between Kirkkonummi and Turku, which leads to a data set of several train / tunnel pressure curves. Finally Gruner Ltd Vienna performed various aerodynamic simulations focussing on aerodynamic loads and pressure comfort considering the higher train speeds in several single bore tunnels on this line.

8. ACKNOWLEDGEMENT

We would like to thank SWECO Infra & Rail Oy, Helsinki and VR Group for their kind permission to publish this work.

9. REFERENCES

[1] Union International Des Chemins Des Fer (UIC)-Code 779-11., "Détermination de laire de la section transversale des tunnels ferroviaires à partir dune approche aérodynamique", Paris, 2005

[2] TSI LOC&PAS, VERORDNUNG (EU) Nr. 1302/2014 DER KOMMISSION über eine technische Spezifikation für die Interoperabilität des Teilsystems „Fahrzeuge — Lokomotiven und Personenwagen“ des Eisenbahnsystems in der Europäischen Union, 18. November 2014

[3] TSI Infrastructure, VERORDNUNG (EU) Nr. 1299/2014 DER KOMMISSION über die technische Spezifikation für die Interoperabilität des Teilsystems „Infrastruktur“ des Eisenbahnsystems in der Europäischen Union, 18. November 2014

[4] EN 14067-5:2006+A1:2010, Railway applications - Aerodynamics, Part 5: Requirements and test pro-cedures for aerodynamics in tunnels; January 2011

[5] Huber A., Langner V., Tunnel Aerodynamics on Costal Line – Full Scale Test, Aerodynamic Analysis – Full Scale Test, Report GRUNER R215’034’000 for SWECO Infra & Rail, Helsinki, 12.01.2022

[6] Vardy, A., Reinke, P., Estimation of train resistance coefficients in tunnels from measurements during routine operation, Proc. Instn. Mech. Enger. Vl 213 Part F, 1999