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Incorporating corrigendum January 2023

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Railway applications — Aerodynamics

Part 5: Requirements and assessment procedures for aerodynamics in tunnels

National foreword

This British Standard is the UK implementation of EN 14067-5:2021, incorporating corrigendum January 2023. It supersedes BS EN 14067-5:2006+A1:2010, which is withdrawn.

The start and finish of text introduced or altered by corrigendum is indicated in the text by tags. Text altered by CEN corrigendum January 2023 is indicated in the text by AC⟩ ⟨AC.

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A list of organizations represented on this committee can be obtained on request to its committee manager.

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Bahnanwendungen - Aerodynamik - Teil 5: Anforderungen und Prüfverfahren für Aerodynamik im Tunnel

This European Standard was approved by CEN on 22 November 2021 and includes the Corrigendum issued by CEN on 11 January 2023.

EUROPEAN COMMITTEE FOR STANDARDIZATION
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Contents

European foreword

This document (EN 14067-5:2021+AC:2023) has been prepared by Technical Committee CEN/TC 256 “Railway applications”, the secretariat of which is held by DIN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by June 2022, and conflicting national standards shall be withdrawn at the latest by June 2022.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN shall not be held responsible for identifying any or all such patent rights.

This document supersedes EN 14067-5:2006+A1:2010.

This document includes the corrigendum EN 14067-5:2021/AC:2023 which corrects some formulas.

The start and finish of text introduced or altered by corrigendum is indicated in the text by tags [AC⟩ ⟨AC].

EN 14067, *Railway applications — Aerodynamics*, consists of the following parts:

- *Part 1: Symbols and units*;
- *Part 3: Aerodynamics in tunnels*;
- *Part 4: Requirements and test procedures for aerodynamics on open track*;
- *Part 5: Requirements and test procedures for aerodynamics in tunnels*;
- *Part 6: Requirements and test procedures for cross wind assessment*.

The results of the EU-funded research project “AeroTRAIN” (Grant Agreement No. 233985) have been used.

The contents of the previous edition of EN 14067-5 have been integrated in this document; they have been re-structured and extended to support the Technical Specifications for the Interoperability of the Trans-European rail system. Requirements on conformity assessment for rolling stock were added.

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

Any feedback and questions on this document should be directed to the users’ national standards body. A complete listing of these bodies can be found on the CEN website.

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1 Scope

This 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. The requirements apply to heavy rail systems only.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 14067-4:2013+A1:2018, *Railway applications - Aerodynamics - Part 4: Requirements and test procedures for aerodynamics on open track*

EN 15273 series, *Railway applications — Gauges*

EN 17149-1:—,[1] *Railway applications — Strength assessment of railway vehicle structures — Part 1: General*

ISO 8756, *Air quality — Handling of temperature, pressure and humidity data*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at https://www.iso.org/obp
- IEC Electropedia: available at https://www.electropedia.org/

3.1
compression wave
approximate step increase in pressure that travels at the speed of sound

3.2
expansion wave
approximate step decrease in pressure that travels at the speed of sound

3.3
computational fluid dynamics
CFD
numerical methods of approximating and solving the formulae of fluid dynamics

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[1] Under preparation. Stage at time of publication: prEN 17149:2021.

3.4
exceptional load

infrequent load which represents the extremal load or combination of loads for the relevant operation conditions, including both steady and transient load

Note 1 to entry: Exceptional load is also described with the terms "static load", "static design load" or "proof load".

[SOURCE: EN 17149-1:—[1], 3.1.9; modified – "including both steady and transient load" added]

3.5
fatigue load

frequent load or combination of loads which represents the normal relevant operation conditions

[SOURCE: EN 17149-1:—[1], 3.1.11]

3.6
steady load

load that is constant or nearly constant with time

Note 1 to entry: These loads include the dynamic pressure due to the airflow acceleration around the front of the train and pressure changes caused by strong side winds.

3.7
transient load

load that varies in time

Note 1 to entry: Transient loads can be divided into three kinds:

a) loads caused by trains crossing with other trains in the open air or due to the pressure field around the train;

b) loads caused by trains travelling alone or crossing with other trains in tunnels;

c) loads that arise due to the turbulent nature of the flow around trains.

Note 2 to entry: Loads a) and b) are relevant for all train structures, but loads c) may be only relevant for some high speed train components and are not considered in this document.

3.8
tunnel

excavation or a construction around the track provided to allow the railway to pass through, for example, higher land, buildings or water

3.9
tunnel length

length of a tunnel is defined as the length of the fully enclosed section, measured centrally at rail level

3.10
tunnel cross-sectional area

free cross-sectional area of a tunnel not including ballast, rail, sleepers, longitudinal piping, platform

3.11
vehicle cross-sectional area

projected cross-sectional area in lengthwise direction of vehicle

3.12
critical crossing

crossing of two trains in a tunnel leading to maximum pressure changes

Note 1 to entry: The terms crossing and passing are used interchangeably in this document.

3.13
gauge pressure

amount by which the pressure measured in a fluid, such as air, exceeds that of the atmosphere

3.14
fixed formation

group of rail vehicles which can only be coupled/uncoupled or assembled/disassembled (e.g. articulated vehicles) in a workshop environment

[SOURCE: EN 17343:2020, 3.1.6.4]

3.15
load collective
pressure spectrum

table of loads and their frequency of occurrence

4 Symbols and abbreviations

For the purposes of this document, the symbols in Table 1 below apply.

Table 1 — Symbols

Symbol	Significance	Explanation or remark	Unit
A_S, A_T	area of integration	see Figure 12	sPa
B	train/tunnel blockage ratio	$B = \frac{S_{tr}}{S_{tu}}$	
b	width of vehicle	see Figure 2	m
C	load collective	see 7.7.4.1	
$C_{f,tr}$	train friction factor or coefficient	see Formula (15)	
$C_{f,tu}$	tunnel friction factor or coefficient		
$C_{lifecycle}$	total load collectives in open air and in tunnels	see Formula (34)	
$C_{lifecycle,front}$	total load collectives in open air and in tunnels at front of train	see 7.7.4.2	
$C_{lifecycle,tail}$	total load collectives in open air and in tunnels at tail of train	see 7.7.4.2	
C_n	factor depending on the shape of the train nose and the shape of the tunnel portal	see Formula (C.2)	
$C_{oa,cros}$	load collective for trains meeting on the open track	see Formula (30)	

Symbol	**Significance**	**Explanation or remark**	**Unit**
$C_{\mathrm{oa,cros},i}$	load collective for trains meeting in segment *i*		
$C_{\mathrm{tu,cross}}$	load collective for passing with crossings in tunnels	see Formula (32)	
$C_{\mathrm{tu,cross},j}$	load collective for passing with crossings in tunnel *j*		
$C_{\mathrm{tu,solo}}$	load collective for solo passages in the tunnel	see Formula (31)	
$C_{\mathrm{tu,solo},j}$	load collective for solo passages in tunnel *j*		
CFL	Courant-Friedrich-Levy number	see 7.6.2	
c	speed of sound		m/s
D_{h}	hydraulic diameter	see Formula (16)	m
d_{x}	measurement distance	see Formulae (21), (22), (23)	m
F_{max}	maximum measured force	see Figure D.4	N
g	gravity		m/s^2
h	height	see Figure 2	m
h_{l}	frequency corresponding to a class of amplitudes in a rainflow matrix	see 7.7.5	
h_0	distance from top of rail to the underside of the vehicle body	see Figure 2	m
h_{c}	height of tunnel centre above rail level	see Figure 1	m
H, $H1$, $H2$	relative humidity of air	see 7.3.2	%
k	S-N curve exponent	see 7.7.5	
k_{r}	vehicle structural rigidity factor	see 7.8.2	
k_1	factor	see Formula (12)	
k_2	factor	see Formula (12)	
k_{s}	train roughness parameter	see 7.3.3	m
L_{n}	nose length of train	see Figure 2	m
$L_{\mathrm{n,model}}$	nose length of train model	see 7.2.7	m
$L_{\mathrm{section,i}}$	length of the route section *i*	see 7.7.4.3	km
L_{tr}	length of train	Length overall	m
L_{tu}	length of tunnel		m
$L_{\mathrm{tu,crit}}$	critical tunnel length	see 7.7.3.6	m
$L_{\mathrm{tu,min}}$	minimum length of a tunnel measured in full-scale tests from entry portal	see Formula (4)	m

Symbol	Significance	Explanation or remark	Unit
$L_{\mathrm{virttun},j}$	virtual length of tunnel j	see Formula (37)	m
$L_{\mathrm{year,e}}$	distance travelled per year on route section i	see 7.7.4.2	km/year
Ma	Mach number		
N_{oa}	number of sections of open track	see 7.7.4.2	1/a
N_{c}	number of cycles of reference value of the fatigue load	see 7.7.5	
$N_{\mathrm{trainsperhour}}$	Number of trains passing a stationary point in one direction per hour	see 7.7.5	1/h
N_{tu}	total number of tunnels on a route	see 7.7.4.2	
$N_{\Delta\mathrm{te},j}$	calculated entry time gaps for j_{th} tunnel	see Formula (33)	
$n_{\mathrm{oa,cros},i}$	frequency for trains crossing on the open track in route section i	see Formula (36)	
$n_{\mathrm{tu,cros},j}$	frequency for trains crossing in the j_{th} double track tunnel	see Formula (38)	
$n_{\mathrm{tu,solo},j}$	frequency of single train passages without train encounter in the j_{th} double track tunnel	see Formula (31)	
Pe_{tr}	perimeter of train		m
Pe_{tu}	perimeter of tunnel		m
p	pressure	see Formula (40)	Pa
p_{eq}	damage-equivalent amplitude	see 7.7.5	Pa
p_{l}	classified pressure amplitude	see 7.7.5	Pa
p_{L}	pressure load	see Formula (24)	Pa
p_{atm}	atmospheric pressure		Pa
p_{d}	pressure difference between external and internal pressure	see 7.1	Pa
p_{e}, $p_{\mathrm{e}}(t)$	external pressure outside of a vehicle, or generated by a train in a tunnel	see 7.1	Pa
$p_{\mathrm{fullscale}}$	full-scale pressures determined from $p_{\mathrm{modelscale}}$	see Formula (19)	Pa
p_{i}, $p_{\mathrm{i}}(t)$	internal pressure in a vehicle, or in an enclosed air volume in a tunnel	see 7.1	Pa
$p_{\mathrm{modelscale}}$	pressures measured at model scale	see Formula (19)	Pa
p_0	reference static pressure		Pa
p_{offset}	offset pressure	see Figure 10	Pa
$p(t)_{\mathrm{sim}}$	pressure signal in tunnel from simulation software	see 7.3.4	Pa

Symbol	Significance	Explanation or remark	Unit
$p(t)_{\mathrm{test}}$	pressure signal in tunnel from track test	see 7.3.4	Pa
r	radius	distance between tunnel exit portal centre and the point of interest, see Figure C.3	m
r_{b}	corner radius of the micro-pressure wave reference vehicle	see Figure 2	m
R	tunnel radius	see Figure 1	m
R_{model}	ratio of full-scale train to its model	see 7.6.3.2	
S_{eq}	equivalent leakage area		m²
S_{tr}	vehicle cross-sectional area	see 3.11	m²
S_{tu}	tunnel cross-sectional area	see 3.10	m²
t, t_{A}, t_{B}, t_{S}, t_{T}	time	see Figures 9 and 11	s
t_{e}	difference in entry time	see 7.7.3.4	s
t_{life}	train service life	see 7.7.4.2	year
$t_{50\ \%}$	time when pressure rise is 50 % of the value at time t_{T}	see Figure 12	s
T	absolute temperature		K
T_{f}	tunnel factor	see Formula (A.26)	
U	local dominant speed (train speed or pressure wave speed)	see 7.6.2	m/s
U_0	flow velocity in tunnel relative to train before train entry	see A.4	m/s
u_0	the measured air flow in a tunnel at the moment of train entry	see 7.3.2	m/s
v_{tr}	train speed		m/s
$v_{\mathrm{tr,1}}$	train speed	see 7.7.4.3	m/s
$v_{\mathrm{tr,2}}$	speed of the encountering train	see 7.7.4.3	m/s
$v_{\mathrm{line,max}}$	design speed of a segment of line	Maximum permitted speed in a defined track segment. The segment may be a tunnel, a line or a segment of a line.	km/h
$v_{\mathrm{tr,max}}$	maximum train speed or design speed of a train	Maximum train speed refers to train operation.	km/h

Symbol	Significance	Explanation or remark	Unit
		If limited by infrastructure, maximum train speed may be lower than design speed.	
$v_{\mathrm{tr,ref}}$	train reference speed		km/h
$v_{\mathrm{tr,test}}$	train test speed	see 7.3.2	m/s
V_{int}	internal volume of the vehicle	see 7.8.3	m^3
X_{d}, X_{h}, X_{fr}, X_{t}	dummy variables	see A.3	
X_{p}	distance between the entrance portal and the measuring position in the tunnel		m
x_1, x_2, x_3	longitudinal positions on the train	defined in 7.7.3.4	m
Y_{tr}	track distance	centre to centre	m
Δh	maximum altitude difference in a tunnel	see 7.2.5	m
ΔL_1	additional length	see 7.2.2.1	m
Δp, $\Delta p(t)$	differential pressure at time t		Pa
Δp_{alt}	natural pressure variation due to altitude	see Formula (9)	Pa
$\Delta p_{\mathrm{d,max}}$	maximum difference between internal and external pressures	see Figure D.4	Pa
Δp_{exit}	amplitude of initial compression wave at the exit portal inside the tunnel	see Formula (C.4)	Pa
Δp_{fr}	pressure change due to friction effects caused by the entry of the main part of the train into the tunnel	see Figure 7	Pa
$\Delta p_{\mathrm{fr,o}}$	pressure change due to friction effects caused by the entry of the main part of the train into the tunnel, measured on the exterior of a train	see 7.2.4	Pa
Δp_{HP}	pressure signature caused by the passing of the train nose at the measurement position in the tunnel	see Figure 7	Pa
$\Delta p_{\mathrm{i,limit}}$	Pressure limit values, i = N, N+fr, N+fr+T	see Table 4	Pa
Δp_{max}	maximum peak-to-peak pressure change on outside of train		Pa
Δp_{N}	pressure change caused by the entry of the nose of the train into a tunnel	see Figure 6	Pa
$\Delta p_{\mathrm{N,o}}$	pressure change caused by the entry of the nose of the train into a tunnel measured on a train on the exterior of the train	see 7.2.4	Pa

Symbol	Significance	Explanation or remark	Unit
Δp_{T}	pressure change caused by the entry of the tail of the train into a tunnel	see Figure 6	Pa
$\Delta p_{\mathrm{T,o}}$	pressure change caused by the entry of the tail of the train into a tunnel measured on the exterior of a train	see 7.2.4	Pa
Δp_1	pressure after train tail entrance	see A.3.2	Pa
$\Delta p_{95\,\%,\mathrm{max}}$	maximimum permissible pressure change	see Formulae (21), (22) and (23)	Pa
$\overline{\Delta p}_{\mathrm{N}}$	average nose entry pressure change	see Table 4	Pa
$\overline{\Delta p}_{\mathrm{fr}}$	average frictional pressure rise	see Table 4	Pa
$\overline{\Delta p}_{\mathrm{T}}$	average tail entry pressure change	see Table 4	Pa
Δt	characteristic time interval for the pressure rise	see Formula (C.2)	s
Δt_e	time increment	see Formula (26)	s
Δx_1	additional distance to ensure a good temporal separation of individual pressure variations	see 7.2.2.2	m
$\varepsilon_{\Delta\mathrm{p}}$	deviation between test and simulation	see 7.3.4	
ζ_{E}	loss coefficient for tunnel portal	see A.3	
ζ_{h}	loss coefficient of the train nose in the tunnel	see A.3	
ζ_{h0}	loss coefficient of the train nose in the open air	see A.3	
ζ_{h1}	coefficient for additional loss of the train nose in the tunnel	see A.3	
ζ_{t}	loss coefficient of the train tail in the tunnel	see A.3	
ζ_{t0}	loss coefficient of the train tail in the open air	see A.3	
ζ_{t1}	coefficient for additional loss of the train tail in the tunnel	see A.3	
ζ_1	loss coefficient for the train	see A.3	
ζ_{N}	train nose pressure loss coefficient	see A.4	
ζ_{p}	tunnel portal pressure loss coefficient	see A.4	
ζ_{T}	train tail pressure loss coefficient	see A.4	
θ_1, θ_2	temperature	see 7.3.2	° C
ρ_{amb}	ambient atmospheric air density	see Formula (12)	kg/m³

Symbol	Significance	Explanation or remark	Unit
ρ_0	Reference air density	1,225 kg/m^3	kg/m^3
ρ, ρ_1, ρ_2	air density ρ_1 in test scenario ρ_2 in reference scenario	see 7.3.2 see 7.3.2	kg/m^3
τ_{dyn}	value of pressure tightness coefficient for moving rail vehicles	see 7.7.3.2	s
τ_{stat}	value of pressure tightness coefficient for static rail vehicles	see 7.8.1	s
Ω	solid angle representing the configuration around the tunnel exit portal	see C.4	
$\overline{}$, (overbar)	average of the value		

5 Requirements on locomotives and passenger rolling stock

5.1 Limitation of pressure variations inside tunnels

5.1.1 General

When a train enters and exits 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.

To define a clear interface between the subsystems of rolling stock and infrastructure in the heavy rail system, 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, two reference cases for rolling stock assessment are defined.

5.1.2 Requirements

5.1.2.1 Reference case

For track gauges from 1 435 mm to 1 668 mm inclusive, the pressure variations generated by a train entering a simple, non-inclined tube-like tunnel, (i.e. without any shafts, etc.), are defined by pressure signatures for two given combinations of train speed and tunnel cross-section. The latter are referred to as the reference cases.

The pressure signature consists of three characteristic pressure variations: Δp_{N} caused by the entry of the nose of the train into the tunnel, Δp_{fr} due to friction effects caused by the entry of the main part of the train into the tunnel, and Δp_{T} caused by the entry of the tail of the train into the tunnel (see Figure 6).

The assessment shall be made for standard meteorological conditions: atmospheric pressure p_{atm} = 101 325 Pa, air density ρ_{amb} = 1,225 kg/m^3, temperature θ = 15 °C with no initial air flow in the tunnel.

Table 2 — Maximum tunnel characteristic pressure changes, Δp_N, Δp_{fr} and Δp_T for the reference case

Maximum design speed km/h	**Reference case**		**Criteria for the reference case, Pa**		
	Reference speed, $v_{tr,ref}$ km/h	S_{tu} m^2	Δp_N	$\Delta p_N + \Delta p_{fr}$	$\mathbf{\Delta p_N + \Delta p_{fr} + \Delta p_T}$
$v_{tr,max} < 200$	**No requirement**				
$200 \leq v_{tr,max} \leq 230$	200	53,6	≤ 1 750	≤ 3 000	**≤ 3 700**
$230 < v_{tr,max}$	250 or $v_{tr,max}$ [a]	63,0	≤ 1 600	≤ 3 000	**≤ 4 100**

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

5.1.2.2 Fixed or pre-defined train compositions

A fixed or pre-defined train composition, running at the reference speed in the reference case tunnel scenario without crossing other trains shall not cause the characteristic pressure variations at a fixed point in the tunnel to exceed the values set out in Table 2.

NOTE 1 Fixed and pre-defined train compositions are described in TSI LOC&PAS 2014, 2.2.1.

For train compositions that are non-symmetrical with respect to running direction, the requirement applies for both running directions. For assessment of symmetry see Table 4, column 1, row 1, excluding the differences that are beneficial.

For fixed or pre-defined train compositions consisting of more than one train unit, the full assessment shall be made for the maximum length of the train of coupled units, see 7.3.

NOTE 2 Full-scale tests provide input data for the assessment and can be carried out using shorter train configurations, see 7.2.2.3.

5.1.2.3 Single rolling stock units fitted with a driver's cab

A single unit fitted with a driver's cab running as the leading vehicle at the reference speed in the reference case tunnel scenario without crossing other trains shall not cause the characteristic pressure variations Δp_N and Δp_T to exceed the values set out in Table 2. The pressure variation Δp_{fr} shall be set to 1 250 Pa for trains with 200 km/h ≤ $v_{tr,max}$ ≤ 230 km/h or, respectively to 1 400 Pa for trains with $v_{tr,max}$ > 230 km/h.

For single rolling stock units capable of bidirectional operation as a leading vehicle the requirement applies for both running directions.

5.1.2.4 Other passenger rolling stock

Other passenger rolling stock running at the reference speed in the reference case tunnel scenario shall not cause the characteristic pressure variations Δp_{fr} to exceed the values set out in Table 2. The pressure variation Δp_N shall be set to 1 750 Pa and Δp_T shall be set to 700 Pa for trains with 200 km/h ≤ $v_{tr,max}$ ≤ 230 km/h or, respectively to 1 600 Pa and 1 100 Pa for trains with $v_{tr,max}$ > 230 km/h.

For passenger rolling stock that is not covered in 5.1.2.2 or 5.1.2.3, conformity shall be assessed for a possible real train configuration, including realistic end vehicles featuring a cab, as close as possible to 400 m train length. If the vehicle might be suitable for train compositions longer than 400 m, the maximum train length, (length of cabs plus rolling stock), shall be determined, which just meets the criterion in Table 2. This maximum train length shall be documented in the vehicle register. See 7.3.6 for scaling for the train length.

5.1.3 Full conformity assessment

A full conformity assessment of rolling stock[2] shall be undertaken according to Table 3.

Table 3 — Methods applicable for the full conformity assessment of rolling stock

Maximum design speed km/h	Methods
$v_{\mathrm{tr,max}} < 200$	No assessment needed
$v_{\mathrm{tr,max}} \geq 200$	Documentation of compliance according to 5.1.4 if applicable; or Full-scale tests according to 7.2.2 and Assessment according to 7.3

5.1.4 Simplified conformity assessment

A simplified conformity assessment may be carried out for rolling stock that is subject to minor design differences by comparison with rolling stock for which a full conformity assessment already exists.

With respect to pressure variations in tunnels, the only relevant design differences are changes in external geometry and differences in design speed and train length.

This simplified conformity assessment shall take one of the following forms in accordance with Table 4:

— a statement that the design differences have no impact on the pressure variations inside tunnels; or

— a comparative evaluation of the design differences relevant to the rolling stock for which a full conformity assessment already exists.

Table 4 — Methods and requirements applicable for simplified conformity assessment of rolling stock

Design differences	Methods and requirements
Differences in external geometry limited to: — reordering in a new consist examined coaches of the same type and/or cross-section; — minor differences in external geometry: — wipers, handles and antennae; — long isolated protruding objects or gaps that are not vertical or close to the front-side radius or edge smaller than 5 cm in the crosswise dimensions; — small isolated protruding objects and gaps smaller than 5 cm in each dimension; — pantographs, electrical wiring and pipes; — other roof and underfloor equipment changes smaller than 20 cm in each physical dimension;	Documentation of differences, statement of no impact and reference to an existing compliant full conformity assessment

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[2] This assessment will comply with the Railway Interoperability Directive.

Design differences	**Methods and requirements**
— addition of equipment fairings greater than 10 m downstream from the tip of the nose; — fittings, seals, bonded joints, handle bars, rear view installations, surface roughness, doors, windows, changes in glazing, signal lights, pipes, cabling and plugs; — other parts with changes in lateral dimensions smaller than 5 cm. — differences that are beneficial: — increase of nose length; — decrease of cross-sectional area; — decrease of train length.	
Other differences in external geometry (e.g. in buffers, front couplers, snow ploughs, front or side windows) keeping the basic nose shape features, in particular the cross-sectional area and the nose length.	Documentation of differences and reference to an existing compliant full conformity assessment AND Assessment of the relative effect of differences by — reduced-scale moving model tests according to 7.2.7 or — three-dimensional CFD simulations according to EN 14067-4:2013+A1:2018, 6.1.2.4 AND evidence and documentation that i) The difference causes changes in each of $\overline{\Delta p}_N$, $\overline{\Delta p}_N + \overline{\Delta p}_{\mathrm{fr}}$, and $\overline{\Delta p}_N + \overline{\Delta p}_{\mathrm{fr}} + \overline{\Delta p}_T$, of less than 5 %. $\left\| \frac{\overline{\Delta p}_{i,\mathrm{B}} - \overline{\Delta p}_{i,\mathrm{A}}}{\overline{\Delta p}_{i,\mathrm{A}}} \right\| < 0,05$ for i = N, N +fr, N+fr+T NOTE Subscript B refers to the new train geometry and subscript A refers to the existing compliant train. and ii) The difference does not exceed 50 % of the margin available on the compliance with 5.1.2, i.e.: $\overline{\Delta p}_{i,\mathrm{B}} - \overline{\Delta p}_{i,\mathrm{A}} < 0,5 \cdot \left(\Delta p_{i,\mathrm{limit}} - \overline{\Delta p}_{i,\mathrm{A}} \right)$ Where values of $\Delta p_{i,\mathrm{limit}}$, i = N, N+fr, N+fr+T, are given in Table 2.

Design differences	Methods and requirements
Increase of: — design speed; — train length.	— Documentation of differences AND — transfer to the reference case by re-scaling methods described in 7.3.2, 7.3.3 or 7.3.4; AND — evidence and documentation that the train still fulfils the requirements listed in 5.1.2.

5.2 Limitation of pressure gradient entering a tunnel (relative to micro-pressure wave generation)

5.2.1 General

When a high-speed train enters a tunnel a compression wave is generated by the piston effect. This compression wave propagates through the tunnel at the speed of sound in front of the train towards the opposite portal. At the opposite portal, the wave is partly reflected back into the tunnel and partly emitted into the environment. The emitted part is called a micro-pressure wave. If the pressure gradient of the compression wave inside the tunnel is sufficiently large, it can cause strong audible effects on people and the environment. Further information is to be found in Annex C.

Therefore, a definition of a reference scenario consisting of a reference train and a reference tunnel is introduced, and the performance of the assessed train is compared to that of the reference train.

5.2.2 Requirements

5.2.2.1 General

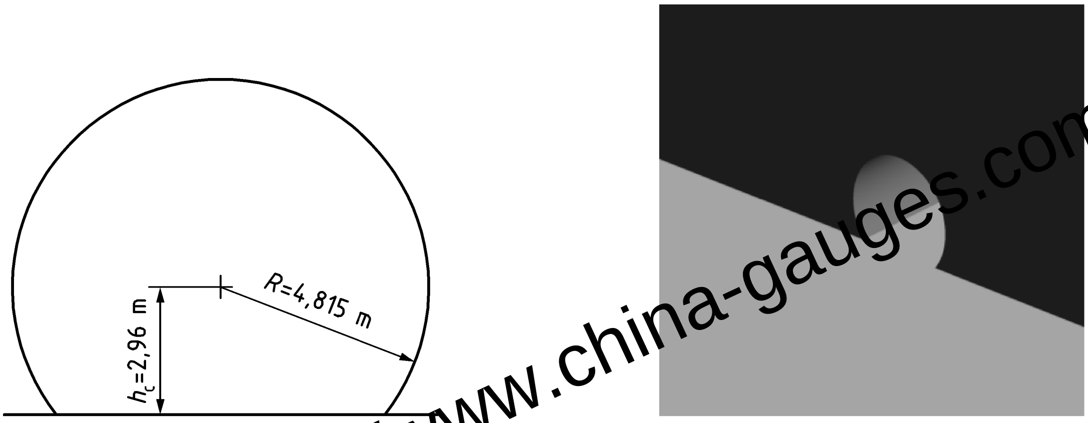
For heavy rail vehicles with track gauges from 1 435 mm to 1 668 mm inclusive it is required to assess the entry pressure gradient and to compare it to the one generated in the reference case.

NOTE The requirement is intended for operation on the European network. Its application to trains operating on limited networks (e.g. no tunnels) can be reassessed.

5.2.2.2 Reference case

The reference case for the tunnel and the train is defined as follows.

The reference tunnel has a free cross-sectional area of 63 m^2. It has a circular shape with a filled lower segment as shown in Figure 1. The portal is set in a vertical wall having at least a radius of 75 m around the tunnel centre. The train shall enter the tunnel centrally. The tunnel length shall be at least 300 m.



a) b)

Key

h_c height of tunnel centre above ground

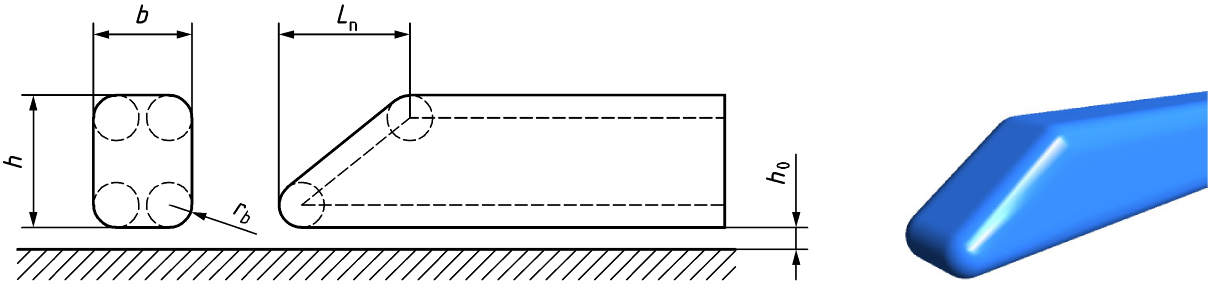
R radius

NOTE The ground level in the reference case models the top of rail when assessing a train.

Figure 1 — Reference tunnel

The reference train is based on simple geometry parameters, as shown in Figure 2. All corners are smoothed by spheres with radius r_b. The body cross-section behind the train nose, with $S_{tr} = 11\ m^2$, remains constant up to the train end. There are no bogies, pantographs or inter-car gaps. The parameters to be used for the reference train geometry are:

$b = 3\ m$, $L_n = 4\ m$, $r_b = 0{,}75\ m$, $h_0 = 0{,}25\ m$, $h = 3{,}828\ m$



a) b)

Key

b width of train

h height

h_0 distance from top of rail to the underside of the vehicle body

L_n nose length

r_b Radius

Figure 2 — Reference vehicle

The reference train shall have the same length as the assessed train. It is sufficient to model just the first 100 m of the trains.

5.2.2.3 Rolling stock units fitted with a driver’s cab

The requirement applies to any vehicle to be operated as a leading vehicle with design speed greater than or equal to 200 km/h, see Table 5.

The requirement applies for each possible running direction.

Table 5 — Methods applicable for the full conformity assessment of rolling stock

Maximum design speed km/h	Method
$v_{\text{tr,max}} < 200$	No assessment needed
$v_{\text{tr,max}} \geq 200$	Assessment by numerical simulation or reduced scale test according to 7.5.

5.2.3 Simplified conformity assessment

A simplified conformity assessment may be carried out for rolling stock units fitted with a driver’s cab that are subject to minor design differences by comparison with rolling stock for which a full conformity assessment already exists. Changes in the basic nose shape features, in particular the cross-sectional area evolution, are generally not considered minor design changes.

With respect to pressure gradient entering a tunnel, the only relevant design differences are differences in external geometry, differences in design speed and equipment in the region of the nose influencing the nose pressure wave.

This simplified conformity assessment shall be made by a statement that the design differences have no impact on the pressure gradient in accordance with Table 6.

Table 6 — Methods and requirements applicable for simplified conformity assessment of rolling stock

Design differences	Methods and requirements
Differences in external geometry limited to: — increases in cross-sectional area less than 1 %; — reductions in nose length less than 2 %, — equipment in the region of the train nose not influencing the nose pressure wave stated as minor differences in external geometry in Table 4.	Documentation of differences, statement of no impact and reference to an existing compliant full conformity assessment having an entry pressure gradient at least 5 % lower than that of the reference vehicle assessment.

5.3 Resistance to aerodynamic loading

5.3.1 General

Aerodynamic loads are caused by the dynamic loads due to trains crossing in the open air, trains running in tunnels, and the steady loads due to the relative airflow over the trains, and include strong wind loads. The loads shall be considered in the construction of rail vehicle bodies, and may be used as aerodynamic loads for strength assessments according to EN 12663-1:2010+A1:2014. The methods to derive loads are suitable for rail vehicle bodies only. They need further adaptation to provide information for the design of smaller train elements such as windscreens, bodyside windows, doors, canopies, fairings or other mouldings attached to the vehicle body.

The most important relevant influencing parameters, not all of which apply to each reference case (see 5.3.2.4, 5.3.2.5 and 5.3.2.6), are as follows:

- natural wind speed;
- maximum line speed;
- train length;
- train cross-section;
- train leading and trailing end shapes;
- maximum train speed;
- comparable parameters of overtaking or crossing trains;
- track spacing (distance between track centres);
- tunnel cross-section;
- tunnel length;
- tunnel type, i.e. single or double track;
- relative entry times of trains entering a tunnel;
- ambient conditions:
  - air density;
  - speed of sound;
  - ambient pressure;
  - ambient temperature;
  - wind (including wind direction, front wind).

5.3.2 Requirements

5.3.2.1 General

For track gauges from 1 435 mm to 1 668 mm inclusive and heavy rail vehicles with design speed greater than 140 km/h, it is required to provide exceptional and fatigue aerodynamic loads for the design of rolling stock. Independently of design speed, this requirement shall also be fulfilled if the heavy rail vehicle is exposed to crossings in tunnels with vehicles running faster than 140 km/h in its standard train operation. The requirement is not applicable to freight wagons.

This document provides exceptional and fatigue aerodynamic loads for rolling stock design, and thereby provides an interface to structural strength assessments according to EN 12663-1:2010+A1:2014. As train parameters influence the loads, the loads shall be assessed individually for the reference cases by use of methods as stated below. For some trains, simplified load cases are provided and can be applied without further assessment steps, see 7.7.7. Furthermore, loads depend on the presence of strong winds, other trains passing on adjacent tracks, as well as the properties of the infrastructure and the train operations. National differences may arise due, for instance, to different vehicle and track gauges.

For vehicle bodies, the exceptional and fatigue aerodynamic load cases defined below are considered to sufficiently cover:

- running in strong winds;
- passing other trains in the open air;
- single train tunnel transit;
- crossing with one other train in a tunnel.

Occupancy of more than two trains may be possible in a very long tunnel. This case is not covered by this document.

The cases above result in an external pressure distribution on the vehicle body. The pressure inside the vehicle adapts to the outside pressure with a time delay dependent on the sealing properties of the vehicle. The difference between the internal pressure, p_i, and the external pressure, p_e, acts as a pressure load, p_L, on all components forming the exterior surface of the vehicle. The body structure of the vehicle shall resist these loads. Due to pressure variations in tunnel operation, the vehicle body is therefore exposed to positive and negative loads.

The following minimum requirements are specified for the determination of the loads. If other parameters are specified or are available from investigations, their use is permitted and shall be documented. The use of more detailed methods is permitted and shall be documented.

Unless otherwise defined, assessments shall be made in standard meteorological conditions, namely: atmospheric pressure p_{atm} = 101 325 Pa, air density ρ_{amb} = 1,225 kg/m³, temperature θ = 15 °C, with no initial air flow in any tunnels considered.

5.3.2.2 Exceptional load cases for vehicle bodies

Exceptional load cases result from operations in:

- the open air in a strong wind;
- in tunnels (worst case condition).

When travelling in the open air, the local load distribution due to strong wind is applied as a static load. It is derived using the reference case for running in strong winds, see 5.3.2.4. In tunnel operation, loads due to the tunnel air flow around the train are considered to be covered by loads in operation in open air with strong wind.

NOTE Although a gust (i.e. transient) wind speed is considered, the associated loading is considered as a static load.

Due to pressure variations caused by operation in tunnels, transient loads act on a train. All relevant operational tunnel scenarios shall be considered and the evaluated maximum load values taken into account in the design of the entire vehicle body. Transient loads due to pressure variation in tunnels are assessed using the reference cases for exceptional loads in tunnels, see 5.3.2.6.

The maximum aerodynamic loads (positive and negative values of p_L) are derived for each case separately. The maximum loads are applied to the vehicle body according to EN 12663-1:2010+A1:2014.

5.3.2.3 Fatigue load cases for vehicle bodies

Fatigue loads result from:

- frequent train passings in open air;
- general operations in tunnels (adverse, but typical scenario).

The basis for determining fatigue loads is an operational scenario with the following parameters which shall be taken into account: for the vehicle (train speed, other various vehicle parameters), for the train route system (tunnels, tunnel dimensions, open air segments, line speed limits, etc.) and for the oncoming traffic (type, speed, passing frequency).

Only transient loads are considered for fatigue loads. The effects caused by transient aerodynamic pressure loads on the vehicle body can, when appropriately combined for a defined operating scenario, represent the loads experienced over the entire life of the vehicle. Depending on the operating scenario under consideration, the load time histories for the following load cases shall be determined:

- Transient loads for passing on open track shall be assessed using the reference case for open air passings, see 5.3.2.5;
- Transient loads in tunnels shall be assessed using the reference case for fatigue loads in tunnels, see 5.3.2.7.

Trains passing in the open or operating in tunnels produce similar stress distributions and can therefore be considered in combination. The relevant effects on the body structure may be combined for instance by use of a rainflow analysis of the pressure curves, see 7.7.4.4. As long as the application meets the specified reference scenarios in accordance with this document, the loads may be regarded as conservative loads for strength assessments according to EN 12663-1:2010+A1:2014.

5.3.2.4 Reference case for running in strong winds (exceptional load case)

The local pressure distribution around the investigated vehicle travelling at maximum design speed in the open air with a steady and uniform wind speed of 30 m/s at wind angles of 0° and 90° causes imposed steady loads on the vehicle body that vary with location. These are referred to as the reference cases for running in strong winds. The loads shall be applied on the vehicle body. Assumptions regarding the position of the vehicle in the train and the properties of other vehicles in the train are allowed in the assessment.

NOTE The wind speed above is a chosen scenario for gust wind conditions considered sufficient for vehicle dimensioning and is not linked to cross wind stability.

5.3.2.5 Reference case for open air passings (fatigue load case)

The pressure field generated by a passing train travelling at maximum line speed on the investigated train in the open air and in the absence of embankments, cuttings and other significant trackside structures is referred to as the reference case.

The position of the investigated vehicle in a train has no influence on the pressure loads caused by the passing train. The imposed loads do depend on the distance between track centres as well as aerodynamic characteristics and speed of the passing train. Adverse aerodynamic characteristics are assumed for the passing train and shall be taken from EN 14067-4:2013+A1:2018, 4.1. The pressure variations generated by the passing train only apply loads on the adjacent side of the investigated train.

As loads from open air passings and tunnel operation are combined in fatigue assessments, the reference case of open air passings is included in the operational reference scenario defined in 5.3.2.7.

5.3.2.6 Reference cases for exceptional loads in tunnel transit

The reference scenario describes train operation in a series of tunnels, with some having other trains crossing. In the reference case, all trains are operated at a speed which is the lowest of i) the stated maximum tunnel speed, ii) the maximum design speed of the investigated vehicle or iii) a project specific speed limitation regarding the speed of crossing trains. The following scenarios with defined parameters for operation speed, tunnel dimensions and train properties are referred to as the reference case.

a) Single track tunnels with cross-sectional tunnel area, S_{tu}, and maximum line speeds, $v_{line,max}$:

- $v_{line,max}$ = 120 km/h, S_{tu} = 32,4 m²;
- $v_{line,max}$ = 160 km/h, S_{tu} = 46,7 m²;
- $v_{line,max}$ = 230 km/h, S_{tu} = 52,0 m²;
- $v_{line,max}$ = 300 km/h, S_{tu} = 59,7 m².

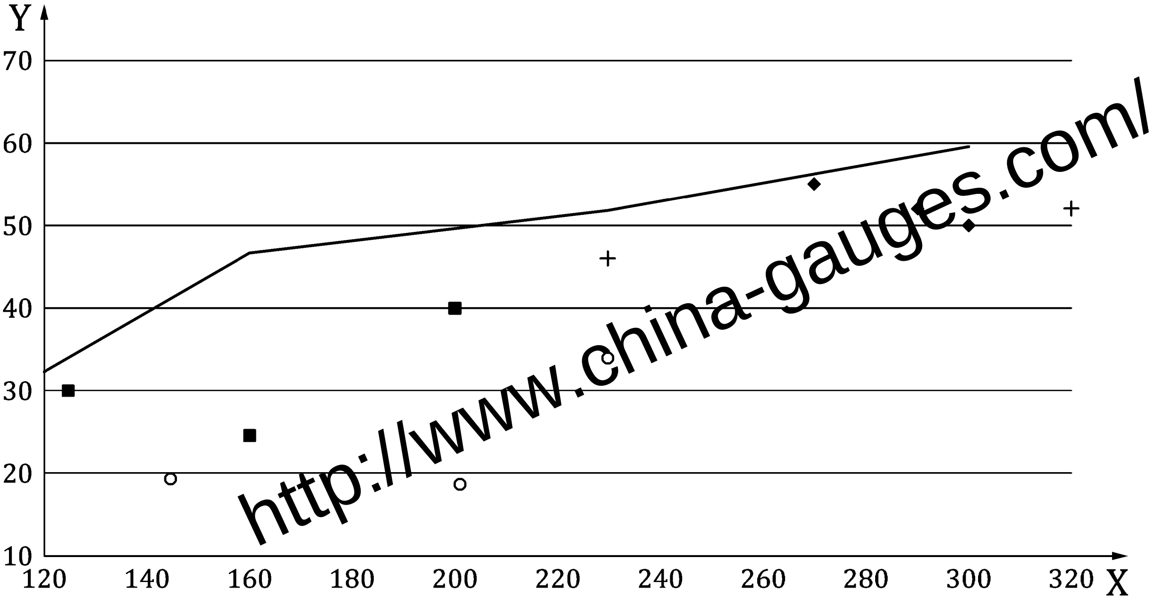
b) Double track tunnels with a maximum speed, $v_{line,max,}$ in the tunnel and cross-sectional tunnel area, S_{tu}, and a passing train class, making full use of the criteria defined in Table 2:

- $v_{line,max}$ = 150 km/h, S_{tu} = 51,0 m²;
- $v_{line,max}$ = 160 km/h, S_{tu} = 74,2 m²;
- $v_{line,max}$ = 200 km/h, S_{tu} = 79,2 m²;
- $v_{line,max}$ = 230 km/h, S_{tu} = 79,2 m²;
- $v_{line,max}$ = 250 km/h, S_{tu} = 82,1 m²;
- $v_{line,max}$ = 280 km/h, S_{tu} = 82,1 m²;
- $v_{line,max}$ = 300 km/h, S_{tu} = 92,0 m².

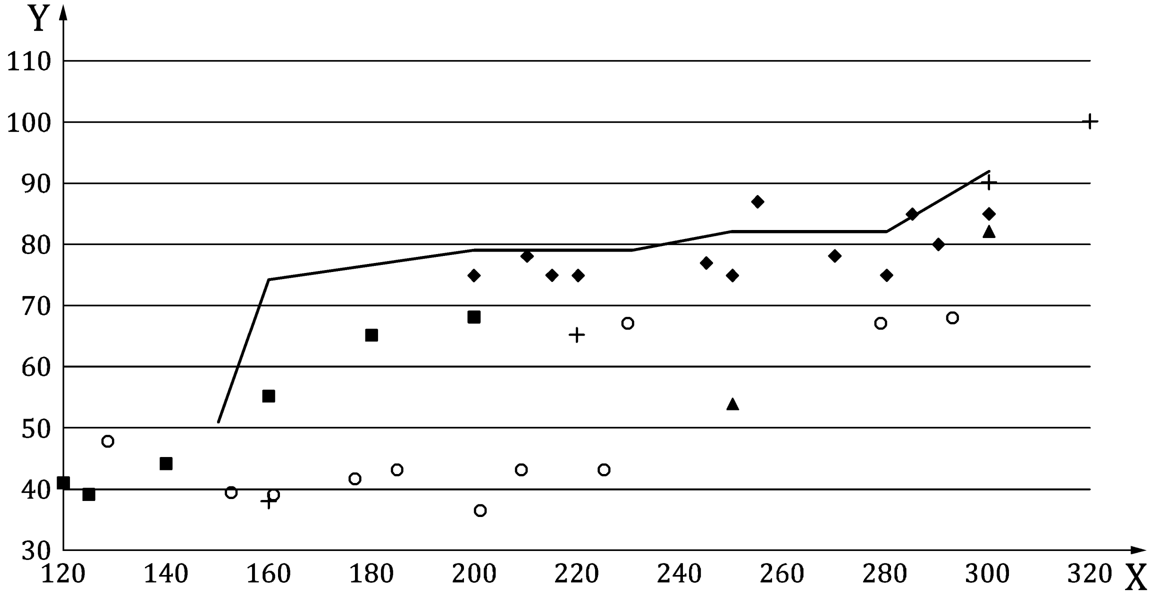
If the operation of the investigated vehicle is for a specific route, where some scenarios are not relevant, they shall be eliminated or replaced. For instance if there are no tunnels on the route, assessment of loads from tunnel scenarios may be ignored.

The above tunnel definitions are considered suitable for Germany. Figure 3 shows cross-sectional areas for single and double track tunnels typical of a number of European countries against the tunnel operating speeds. The reference cases above are shown as lines connecting the symbols. Unless there are reference cases defined on national or network level, reference cases may be derived to model the intended operation of the vehicle.

NOTE Information on tunnel length and cross sections can be found in the register of infrastructure according to "Commission Implementing regulation (EU) 2019/777 of 16 May 2019 on the common specifications for the register of railway infrastructure", see guide in [21].



a) Single track tunnels

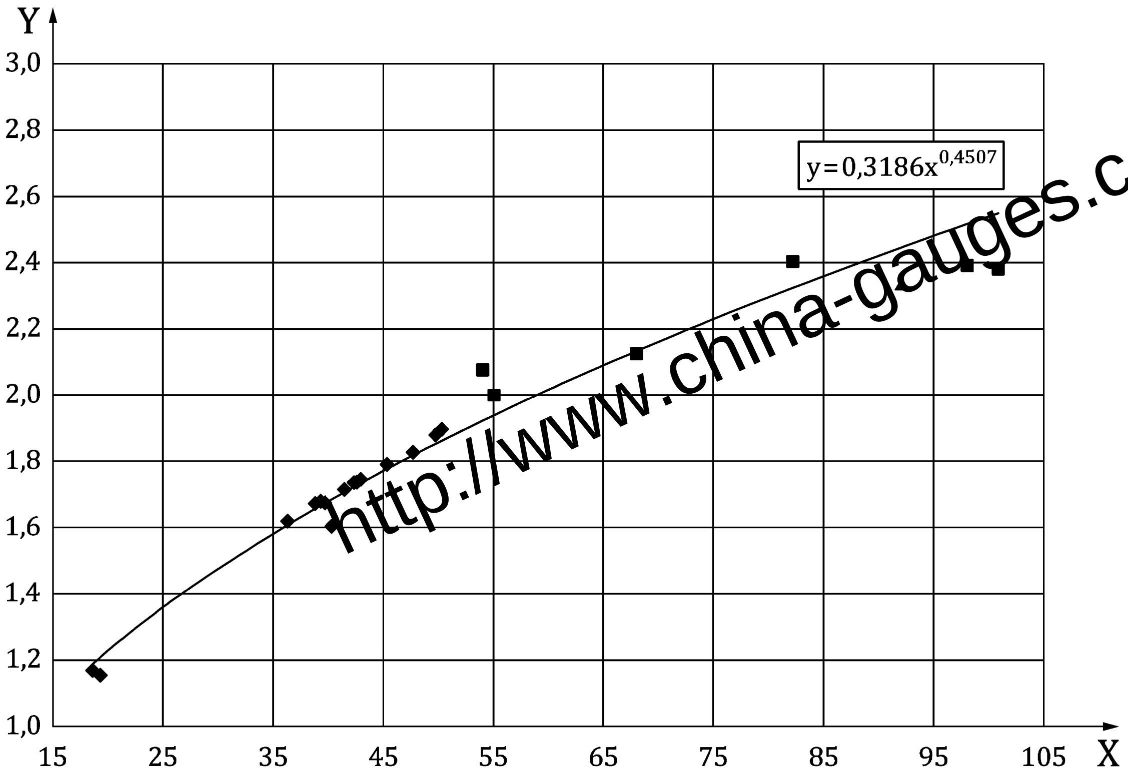


b) Double track tunnels

Key

X	v_{tr}, [km/h]
Y	S_{tu}, [m^2]
—	CEN/Germany
+	France
◆	Spain
○	Great Britain
■	Switzerland
▲	Italy

Figure 3 — Cross-sectional areas for single and double track European tunnels



Key

X S_{tu} [m^{2}]

Y $S_{\mathrm{tu}}/Pe_{\mathrm{tu}}$ [m]

◆ Great Britain

■ Italy

▲ Germany

— Power law

Figure 4 — Tunnel area to perimeter ratios

Figure 4 shows a plot of the tunnel area to perimeter ratio against tunnel area, based on national database values, which is useful when only tunnel area values are available.

Transient pressures in tunnels shall be assessed for the investigated vehicle running in a train. The tunnel length is chosen to be the critical length based on the maximum external pressure change according to 7.7.3.6.

5.3.2.7 Reference cases for fatigue loads in tunnel transit

A scenario with defined parameters for trains, operation and infrastructure as listed below is referred to as the reference case. The reference scenario describes a train operation on a railway line with tunnels and train crossings. In the reference case, the vehicle is assumed to operate for its full life-time solely on the railway line described by the reference scenario. In this operation, the vehicle's external surface is exposed to numerous pressure variations. Differences between the external and internal pressures act as transient loads on the vehicle body, and therefore depend on the degree of pressure sealing of the investigated vehicle.

The various pressure differences between the external and the internal pressures and their frequency of occurrence during the vehicle's life-time are represented by a load collective. The load collective representing a life-time operation according to the reference scenario shall be applied as a fatigue load to the vehicle body.

Until the development of standard reference scenarios, the scenarios should be specified in the vehicle specification. If a reference scenario is to be representative for a railway network and not just a specific line, justification shall be made to demonstrate that the chosen reference scenario contains sufficiently demanding fatigue loads to be representative of the different segments (i.e. tunnels, open air) of the network.

The generic reference scenario is defined by the following parameters describing operation of the investigated vehicle on a railway line for each segment of line:

- Infrastructure parameters (per segment):
  - length of a track segment, $L_{\text{section},i}$, and indicator whether it is open air or tunnel;
  - maximum line speed, $v_{\text{line,max}}$;
  - tunnel free cross-sectional area, S_{tu};
  - number of tracks and distance between track centres.
- Operational parameters:
  - operation in both directions on the defined infrastructure during the life-time of vehicle;
  - number of trains passing a stationary point in one direction per hour $N_{\text{trainsperhour}}$.
- Train parameters:
  - the speed of trains crossing is equivalent to maximum line speed, if not defined differently;
  - aerodynamic characteristics of trains crossing in tunnels, as defined by the limit values in Table 2 in 5.1.2.1;
  - aerodynamic characteristics of trains passing in the open air, as defined by EN 14067-4:2013+A1:2018, Table 2.

The required parameters of the investigated vehicle are introduced in 7.7.3.2.

NOTE A reference scenario for the German network is defined in [9] and [10].

5.3.3 Exceptional load assessment

A full exceptional load assessment of rolling stock shall be undertaken according to Table 7.

Table 7 — Methods applicable for the full exceptional load assessment of rolling stock

Criteria	Methods
Rail vehicles with — non-pressure tight design (see 7.7.3.2) and — $v_{\mathrm{tr,max}} \leq 200$ km/h and — operation only on railway lines with $v_{\mathrm{line,max}} \leq 200$ km/h.	**Assessment of exceptional loads by** **— simplified load case according to 7.7.7.2**
Any other rail vehicle	**Assessment of** **— load due to operation in strong wind according to** 7.7.1 **and** **— exceptional transient loads in tunnel according to 7.7.3.**
NOTE The term 'non-pressure tight' is used equivalently to 'unsealed', and 'pressure tight' equivalently to 'sealed' in this document.	

5.3.4 Fatigue load assessment

A full fatigue load assessment of rolling stock shall be undertaken according to Table 8.

Table 8 — Methods applicable for the full fatigue load assessment of rolling stock

Criteria	Methods
Rail vehicles with — non-pressure tight design and, — $v_{\mathrm{tr,max}} \leq 200$ km/h and — operation only on railway lines with $v_{\mathrm{line,max}} \leq 200$ km/h.	Assessment of fatigue loads by — simplified load case according to 7.7.7.3
Any other rail vehicle	Assessment of — fatigue loads due to trains crossing in open air according to 7.7.2 and — fatigue loads due to operation in tunnels according to 7.7.4**.**

5.3.5 Assessment in case of modification

A simplified load assessment may be carried out for rolling stock that is subject to minor design differences when compared to rolling stock for which a full load assessment already exists.

The only relevant design differences are differences in train design speed, changes in the route characteristics, and changes in the pressure tightness of the investigated train, which will only be significant if they impact on the aerodynamic load collective or on the strength analysis.

This simplified conformity assessment shall take one of the following forms:

- a statement that the differences have no impact on the load collective or strength analysis;

- a comparative evaluation of the design differences from the rolling stock for which a full conformity assessment already exists.

6 Requirements on infrastructure

6.1 Limitation of pressure variations inside tunnels to meet the medical health criterion

6.1.1 General

Any tunnel or underground structure shall be designed such that the maximum pressure variation caused by the passage of trains running at the maximum permitted speeds do not exceed 10 kPa on the train, to meet the medical health criterion. Respecting the criterion leads to different requirements according to whether the tunnel is single or double tracked. This is because for a single track tunnel the maximum pressure variation will be the same for every train passage for a particular train at a given fixed speed, whereas for a double track tunnel the maximum pressure variation will also depend on the crossing train and its relative entry time.

The pressure variation shall be evaluated outside the train under the assumption of a scenario involving a total failure of the train's pressure sealing such that pressures in the train are the same as those outside the train.

NOTE 1 Fulfilling the above requirements for passengers does not ensure the criterion is met for trackside workers inside the tunnel itself. Workers safety is not dealt with in these requirements.

The scenarios to be investigated involve trains in the reference cases generating pressures according to Table 2.

NOTE 2 The 10 kPa pressure change limitation is not, in general, sufficient to properly design a tunnel. For other considerations, see 6.2 and 6.3.

6.1.2 Requirements

6.1.2.1 Reference case

For track gauges from 1 435 mm to 1 668 mm inclusive, the assessment of maximum pressure variations on the outside of the train at the positions x_1, x_2 and x_3 (see 7.7.3) shall be undertaken using methods according to 7.4. The train input parameters to be used are to be such that the reference characteristic pressure signature of the trains is defined by the limit values set out in Table 2 according to the maximum design speed in the tunnel.

The train reference cross-sectional area is considered constant. For the maximum gauge of the rolling stock to be operated the cross-sectional area is taken to be:

a) 12 m^2 for vehicles designed for GC, DE3 and GEC16 gauges;

b) 11 m^2 for vehicles designed for GA, GB, GHE16, GEA16 and GEB16 gauges;

c) 10 m^2 for vehicles designed for G1 gauges.

For other rolling stock gauges according to the EN 15273 series, a reference cross-sectional area shall be determined.

Two train lengths shall be used in the assessment; 200 m and 400 m. The 200 m reference train shall match the criteria in Table 2 with the same frictional effects per coach as the 400 m train specified. For double track tunnels, two crossing cases in the tunnel shall be considered; the critical crossings of two 400 m length trains and two 200 m length trains. The assessment shall consider the named construction features given in Table 9, which also details features which may be ignored.

The pressure variation shall be assessed during the passage of the whole train through the tunnel.

NOTE For single track tunnels the assessment of the whole tunnel is needed, as the pressure peaks are far apart. For double track tunnels the peaks are closer, but it is convenient and considered accurate to use the same time interval of t_e, see Formula (26).

The pressure variations due to weather conditions outside the portals shall be neglected.

The assessment shall be made for standard meteorological conditions: namely atmospheric pressure p_{atm} = 101 325 Pa, air density ρ_{amb} = 1,225 kg/m^3, with no initial air flow in the tunnel and an air temperature of θ = 15 °C.

For infrastructure assessment, any train meeting the values stated in Table 2 shall be considered as a reference train.

Table 9 — Construction features which shall or may not be considered

Features that shall be considered	Features that may be ignored
airshafts	increases in tunnel cross sectional area due to track curvature
changes of cross sectional area in the tunnel over a length greater than 20 m	individual pieces of equipment, e.g. signal masts, electrification masts, overhead contact line equipment
continuous equipment along through the tunnel, e.g. cable troughing, cables, water pipes if the resulting impact on the blockage ratio is more than 1 % to 2 %	specific cross-sectional changes less than 0,15 S_{tu} due to e.g. niches/refuges
emergency walkways or evacuation platforms	portal geometry design
open cross connections and crossovers between tunnel bores	
length of portal hoods if present	
elements that contribute to the friction of the tunnel such as roughness of the tunnel wall, ballast and rails, the frictional effects of niches and recesses, etc.	

6.1.2.2 Single track tunnels

The effects of tunnel inclination due to track gradient shall be included.

Pressures shall be assessed over the time period of the full train passage through the tunnel.

6.1.2.3 Double track tunnels

The effects of tunnel inclination shall not be included.

Pressures caused by crossing trains shall be investigated by systematically varying the relative entry times of two trains into the tunnel. The pressure variation shall be assessed during the tunnel passage of the whole train on which the pressures are analysed.

Predictive formulae (see 7.2.5), using critical pressure wave interaction scenarios, may be useful during the pre-design phase.

Trains travelling in the same direction do not have to be analysed.

6.1.2.4 Multi-track tunnels

A tunnel with more than two tracks may be assessed as a double track tunnel. Justification that this is sufficient shall be provided for this approach.

6.1.3 Full conformity assessment

A full conformity assessment of tunnels shall be undertaken according to Table 10.

Table 10 — Methods applicable for the full conformity assessment of tunnels

Design speed of the tunnel $v_{\text{line,max}}$ km/h	**Tunnel length** m	**Methods**
$v_{\text{line,max}} \leq 160$	$100 < L_{\text{tu}} \leq 12\ 000$	— No requirement if $B \leq 33$ %, — Assessment of maximum pressure change according to 7.4 for $B > 33$ %
any	$L_{\text{tu}} \leq 100$	No requirement
$160 < v_{\text{line,max}}$	$100 < L_{\text{tu}} \leq 12\ 000$	Assessment of maximum pressure change according to 7.4
any	$L_{\text{tu}} > 12\ 000$	specific investigations

Tunnels that are longer than 12 000 m shall be assessed by a specific investigation of the maximum pressure changes, see Table 10. This investigation shall include consideration of crossing trains in double track tunnels and multiple train occupancies. Specific investigations may also be applied to tunnels of length less than 12 000 m where there are special conditions expected to exist in the tunnel, i.e. high altitude tunnels or geothermal effects in the tunnel.

6.1.4 Simplified conformity assessment

A simplified conformity assessment may be carried out for a tunnel that is subject to minor design changes for which a previous full conformity assessment with respect to pressure variations already exists. The only relevant design differences are differences shown in the right-hand column of Table 9 together with tunnel speed reduction. This simplified conformity assessment shall take one of the following forms in accordance with Table 11:

— a statement that the design changes have no adverse impact on the pressure variations inside tunnels;

— a comparative evaluation of the design changes relevant to the tunnel for which a full conformity assessment already exists.

Table 11 — Methods and requirements applicable to simplified conformity assessment of tunnels

Design differences	**Methods and requirements**
Changes in tunnel design limited to features indicated in the right-hand column of Table 9. Reductions in tunnel line speed.	Documentation of changes, statement of no impact and reference to an existing compliant full conformity assessment.

6.2 Limitation of pressure gradient entering a tunnel (relative to micro-pressure wave generation)

6.2.1 General

As the adverse effects of micro-pressure wave emissions are primarily of an acoustic nature, any limitation to micro-pressure wave emission, if applicable, is expected to be regulated by national noise rules.

NOTE 1 Although in European countries noise emission rules may exist for railway operations; currently no standardized rules suitable for micro-pressure emissions are available. In Germany, a guideline exists which covers the infrastructure assessment and acoustic criteria [3].

The method and requirement below ensure that, in an investigation of a tunnel regarding micro-pressure wave emissions, the interface between infrastructure and rolling stock defined in this document is considered. Following this, the operation of any train compliant to 5.2 in a tunnel is compliant to national noise requirements (if available) without further assessment. It is thus not necessary to investigate actual trains intended for operation, if the tunnel is assessed considering only the reference train.

NOTE 2 This section deals with only the pressure wave generated on entry of a train into a tunnel portal. It does not provide methods to investigate the propagation and steepening of the pressure wave travelling through the tunnel and the emission of micro pressure waves.

6.2.2 Reference case

For track gauges from 1 435 mm to 1 668 mm inclusive, the reference case is described in 5.2.2.1.

6.2.3 Requirements

If a tunnel of the heavy rail system is assessed regarding micro-pressure wave emissions, the pressure gradient generated by the reference train defined in 5.2.2.1 shall be applied. If the tunnel is not then compliant to (any) national conformity rules on micro-pressure wave emissions, the tunnel design shall be modified to ensure operation of the reference train and all rolling stock compliant to the requirement in 5.2.

6.2.4 Assessment

An assessment shall be performed using the methods stated in Table 12. The maximum line speed $v_{\text{line,max}}$ refers to the entry speed at the tunnel portals.

Table 12 — Methods applicable for the full conformity assessment of infrastructure

Maximum design speed km/h	**Method**
$v_{\text{line,max}} < 200$	No assessment needed
$v_{\text{line,max}} \geq 200$	Assessment by numerical simulation or reduced scale test according to 7.6.

6.3 Further aspects of tunnel design

6.3.1 General

The following additional aspects should be considered in the design of tunnels and operations therein to facilitate efficient operation. National methods and criteria are not currently harmonized.

6.3.2 Aural pressure comfort

The level of aural pressure comfort offered to people travelling on a train through a tunnel is the choice of the operator. The level of pressure tightness of the train influences the degree of pressure comfort that can be achieved.

Minimum pressure comfort criteria for sealed and unsealed trains are suggested in Annex B. Methods to assess the pressure sealing of rolling stock are given in 7.8.

Infrastructure managers should provide a network that allows operations with sufficient pressure comfort using common rolling stock. When designing a new tunnel, the tunnel free cross-sectional area, the target train speed and its pressure sealing in the tunnel, and the degree of pressure comfort aimed at shall be considered together to achieve the best compromise. For tunnels with lengths less than 50 m pressure comfort does not need to be considered.

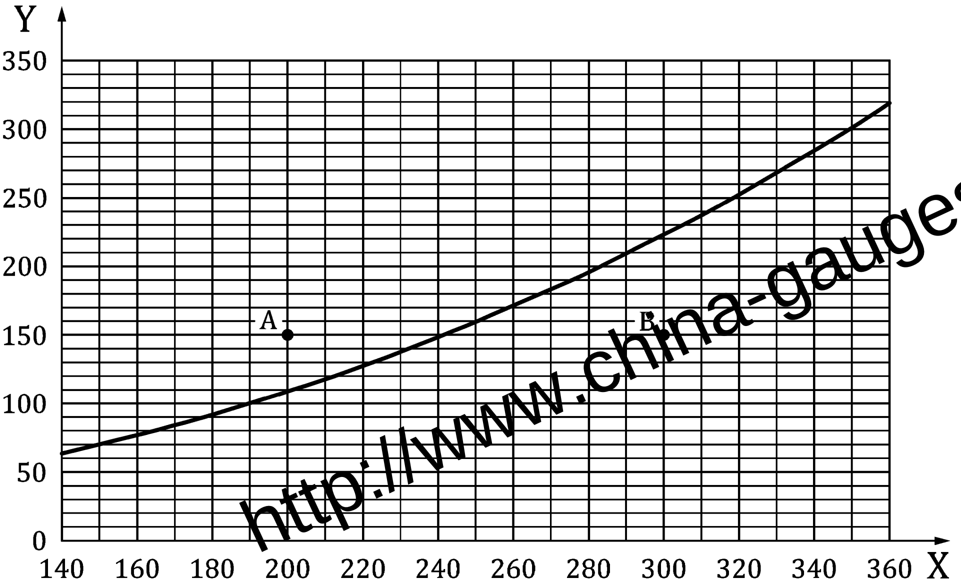
If trains with different degrees of pressure sealing are planned for the new tunnel, the pressure comfort should be based on the least sealed train crossing with itself and with the other trains.

For a new train operation in an existing tunnel, the train sealing efficiency and train operating speed shall be balanced in order to achieve a particular level of pressure comfort. Consideration shall also be given to the pressure comfort of passengers in trains already using an existing tunnel, particularly if the new train operation is planned to operate at a higher speed.

When assessing the pressure comfort, the dynamic pressure tightness, $\tau_{\mathrm{dyn},}$ as well as the pressure management system shall be taken into account, if applicable.

Overbridges may be sufficiently long as to be considered a tunnel according to the definition used in this document. However, their cross-sectional areas may also be so large that aerodynamic pressures generated by trains passing through them will not create an aural pressure comfort problem. Figure 5 conservatively shows when the area of a tunnel or over-bridge is large enough that pressure comfort issues need not be determined, as a function of train speed; effectively defining tunnels and over-bridges in terms of area.

Figure 5, shows with points A and B two examples for structures given train speeds and cross-sectional areas. Point A is above the curve and so pressure comfort can be ignored due to the large cross-sectional area. Point B is below the curve, so pressure comfort should be considered.



Key

X v_{tr}, km/h

Y S_{tu}, m^2

___ boundary between tunnels and overbridges

A example of overbridge

B example of tunnel

Figure 5 — Definition of overbridge with train speed for underground structures with lengths of 50 m and greater

6.3.3 Pressure loading on installations

During tunnel passage a train creates pressure changes inside the tunnel. These pressure changes can be split into the pressure changes due to the near flow field of the train during passage, and the pressure changes that a train creates while entering or leaving a tunnel (i.e. pressure waves).

The pressure changes due to train passage depend on the aerodynamic characteristics of the trains passing through or crossing, the train speed, the geometry and blockage ratio of the tunnel.

NOTE Further information on the characteristics of trains is provided in 5.1.2.

Pressure changes may induce loads on fixed installations in the tunnel if they contain or separate air volumes (e.g. cabinets, tunnel doors) from the air in the operated tunnel. The loading on such equipment shall therefore take into account its pressure sealing. (If the degree of sealing is unknown, a conservative assumption is that the sealing is perfect).

For the design of a component inside a tunnel, exceptional pressure loads and fatigue pressure loads for the component‘s lifetime shall be considered.

For a specific single-track tunnel, the exceptional pressure load shall be determined by using the train characteristics as specified in 5.1.2 and the maximum tunnel operating speed. At the most adverse positions in the tunnel, this load may occur frequently.

For a double-track tunnel the exceptional pressure load shall be determined by using the train characteristics as specified in 5.1.2, the maximum tunnel operating speed and the evaluation of the critical crossing situation, see 7.1.

For a fatigue analysis an operational scenario shall be analysed.

6.3.4 Induced airflows

The movement of trains in tunnels induces air movements along the tunnels, through portals and any open cross-passages if present, and up and down any existing airshafts. These airflows can reach high peak values (>30 m/s), particularly in shafts and cross-passages, depending on train speeds and the tunnel design. It is possible that such high air speeds may cause noise problems in certain designs of airshaft.

Smaller airflows are generated by atmospheric pressure differences between the portals of the tunnel and air density differences due to temperatures inside and outside the tunnel, or altitude differences between the portals.

These airflows shall be considered for the safety of any personnel working in the tunnel e.g. by the provision of niches, handholds.

Also, equipment installed in the tunnel, such as signal gantries or catenary supports, with areas exposed to longitudinal airflow shall withstand any airflow induced loads.

6.3.5 Aerodynamic drag

A train running in a tunnel displaces air in front of it and back to its rear. This results in an air flow over the train opposing the direction of travel that increases skin friction forces compared with the open air. Also, in tunnels the train shall overcome the pressure difference between the nose and the tail. Both effects result in an increase of aerodynamic drag when a train is running in a tunnel. To maintain full operational speed in a tunnel, the additional drag needs to be compensated by the traction system of a train, resulting in an increase in energy consumption. The predictive formulae in A.3.6 or numerical simulation software (see 7.2.6) may be used to estimate the aerodynamic drag of trains in tunnels.

6.3.6 Contact forces of pantograph to catenary

Upon tunnel entry, the displacement of air along a train opposing the direction of travel increases the speed of the air flow around the pantograph. As all pantographs generate aerodynamic lift forces, contact forces between the pantograph and the overhead contact line may increase, especially in tunnels with small blockage ratios, B. The mechanical dimensioning of the catenary shall be checked to account for any increase in contact force.

6.3.7 Ventilation

Trains operating in tunnels induce airflows that facilitate fresh air entering the tunnels. Natural ventilation is induced by total pressure differences between the portals. Such induced airflows may have to be considered in the design of any artificial ventilation system.

For very long or intensively operated tunnels, the air temperature may also increase due to heat generated by trains or rock temperature due to geothermal effects, which may affect personnel or technical installations. The design of the ventilation system should consider such temperature increases.

6.3.8 Workers’ safety

If workers are allowed in tunnels during commercial operation, it is recommended that the assessment of workers' safety should include the following aspects:

— pressure changes;

— air velocities;

— air quality (exhaust gases, dust, carbon monoxide, carbon dioxide, etc. from combustion engines such as diesel locomotive-hauled trains, plant equipment).

6.3.9 Loads on vehicles in mixed traffic operation

Mixed operation describes the operation of high speed trains (above 200 km/h) together with trains designed for speeds lower or equal to 200 km/h on the same track. The latter trains, in this context, are trains for freight transport and/or passenger transport, such as regional or commuter trains. They may experience significantly larger loads in double track tunnels, if crossing with high speed trains running faster than 200 km/h

It is recommended to investigate the maximum operational speeds for mixed traffic in tunnels, if the combination of essential design parameters such as maximum line speed, minimum distance between track centres, minimum tunnel cross-sectional area and rolling stock gauge are not covered clearly by trouble-free operational experience. This may also apply to operation on open track.

The aerodynamic loads on enclosed freight wagons, like sliding door wagons, are described in Annex D. For freight trains, there is no common criterion regarding the aerodynamic loads that freight vehicles may withstand safely. The technical standards for freight trains, see EN 12663-1:2010+A1:2014 and EN 12663-2:2010, which have been derived from operational experience, ensure a certain robustness of the different installations on freight vehicles. Assessments of mixed operations with freight trains should therefore provide comparisons of load cases referring to existing tunnel crossing scenarios with trouble-free operational experience.

For high-speed lines with double-track tunnels operated above 200 km/h, it is recommended to include in the railway network statement for passenger trains structural requirements according to 5.3 and EN 12663-1:2010+A1:2014 or other applicable rules.

6.4 Additional aspects for underground stations

6.4.1 Pressure changes

Pressure changes generated by the trains operating in tunnels attached to underground stations may act on passengers (medical safety, pressure comfort), installations (pressure loads, micro-pressure waves) and doors (rapid door movements) in the stations and the connected pedestrian tunnels. Large pressure changes are generated by the entry of a train at high speed from the open air into a tunnel and proceed into a connected underground station.

It is recommended to investigate the need for pressure relief shafts in the station if the combination of essential design parameters, such as maximum line speed, minimum tunnel cross-sectional area, rolling stock gauge and general layout of the tunnel-station-system do not clearly result in trouble-free operational experience.

6.4.2 Induced airflows

Air flows are generated by trains operating in tunnels (due to the piston effect) attached to underground stations and their pedestrian tunnels, as well as in the near flow field of trains passing by platforms (slipstream effects).

Air flows may result in the discomfort of passengers exposed to them, especially in waiting areas. Very high air speeds may affect the stability of passengers standing on platforms or generate a potential risk, if unguarded wheeled vehicles (e.g. wheelchairs, pushchairs, suitcases on wheels) are set in motion and roll towards the track.

Airflows create loads on installations in the station and connecting tunnels.

6.4.3 Specific case for loads on platform barrier systems due to trains passing

As described in 6.3.3 and 6.4.1, instantaneous pressure changes will also occur on the trackside surfaces of platform barrier system due to the passing of the nose, the tail and the inter-car gaps of the train. In general, a pressure load acts perpendicular to the platform barrier because of pressure differences across both sides of the barrier. Due to the relatively small distances between platform barriers and the centre of track, load cases given for flat structures parallel to the tracks in EN 14067-4 are not applicable.

As the loads depend strongly on the individual design, only the principles for the choice of a scenario and an approach for assessment to derive the loads are defined.

The following parameters have significant effects on the magnitude of loads:

- the geometry of train nose, intercar gaps and tail, rolling stock gauge;
- the geometry of platform barrier system;
- the distance of the barrier from the sides of passing trains;
- the geometry of surrounding infrastructure;
- the geometry of pressure relief openings in the platform barrier system, if fitted;
- the maximum train speed.

Aerodynamic loads on platform barrier systems shall be derived for a scenario chosen taking into consideration all of the above stated parameters.

A blunt nose train geometry resulting in large pressure changes shall be derived, justified and used as a reference train. For the heavy rail network and when the maximum line speed is greater than 160 km/h, the train geometry shall meet the criteria provided for Δp_N in Table 2.

The investigated geometry of the platform barrier system, the infrastructure and pressure relief openings shall be chosen appropriately and justified. The aerodynamic load used in structural assessments for fatigue shall include, as a minimum, the loads due to nose and tail passage with an appropriate number of train passings, and loads due to pressure waves in the tunnel/station system.

Exceptional load cases for platform barriers in subterranean stations with connecting tunnels and in the open air shall be chosen appropriately and justified. For platform barriers in the open air, loads as described in 6.4.1 are not applicable.

7 Methods and test procedures

7.1 General

Pressure variations are described by means of the gauge pressure, $p(t)$, measured in time and referenced to atmospheric pressure, (for standard meteorological conditions the atmospheric pressure p_{atm} = 101 325 Pa).

The external pressure, p_e, usually denotes the pressure outside a train, or equally inside a tunnel as generated by a train passing through the 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.

$$p_d = p_e - p_i \quad (1)$$

NOTE On some occasions it can be useful to define the pressure difference in reverse, i.e. see static pressure load p_L in 7.7.3.1

The definition of p_d shall be documented.

An example of the pressure difference on a well-sealed train in two successive tunnels is shown in Figure 6.

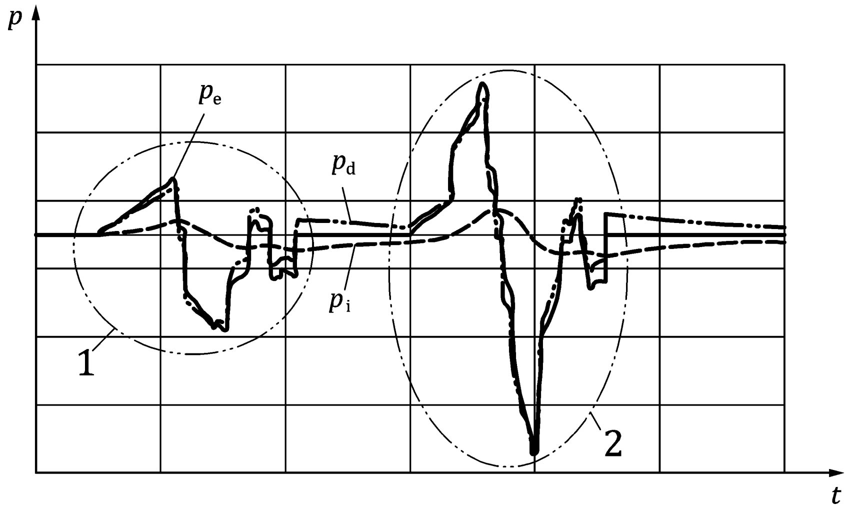
Besides the vehicle and tunnel parameters (as detailed in Clause 5 and 6), the pressure variation depends on the operational mode, especially for a single train running or trains crossing, in the tunnel.

Train crossings include not only the situation when both trains are present simultaneously in the tunnel, but also for the period after the first train has left the tunnel and residual pressure waves are still propagating, although damped e.g. by friction and portal losses. This complete scenario is denoted here as aerodynamic crossing, and can be described e.g. by a virtual tunnel length which comprises a period when wave propagation is still significant after the first train has left, see 7.7.4.3.

Each pressure variation is distinct for specific combinations of vehicle, tunnel and operational conditions. Certain combinations of train speeds, relative entry time and tunnel lengths, lead to maximum pressure changes; such combinations are referred to as critical crossings.

Different methods, (such as full-scale measurement, reduced scale measurement, numerical simulation or predictive formulae), may be used to determine the pressure variations in tunnels related to specific requirements. Other computational or analytical methods may be used to analyse the data or to obtain required parameters. Those methods are described in the following clauses.

The method used shall be documented and an error assessment shall be carried out when required in subclauses.



Key

1	*single* train transit
2	critical crossing with two trains
p_e	external pressure
p_i	internal pressure
p_d	pressure difference between external and internal pressures

Figure 6 — Pressure difference on a well-sealed train in two successive tunnels

7.2 Methods to determine pressure variations in tunnels

7.2.1 General

7.2 describes methods that may be applied for several purposes to determine pressure variations in tunnels.

- The static pressure in the tunnel as shown in Figure 7 develops as follows when a train enters the tunnel:
- first there is a sharp increase in pressure Δp_N caused by the entry of the nose of the train into the tunnel;
- then there is a second increase in pressure Δp_{fr} due to friction effects caused by the entry of the main part of the train into the tunnel;
- then there is a drop in pressure Δp_T caused by the entry of the tail of the train in the tunnel;
- then there is a sharp drop in pressure Δp_{HP} caused by the passing of the train nose at the measurement position in the tunnel.

Real measurements of pressures may differ from the idealized pressure signature shown in Figure 7, for instance if the train cross-sectional area varies along the train. In such a case, special consideration shall be given to determining the individual Δp values.

All Δp values shall be considered as absolute values.

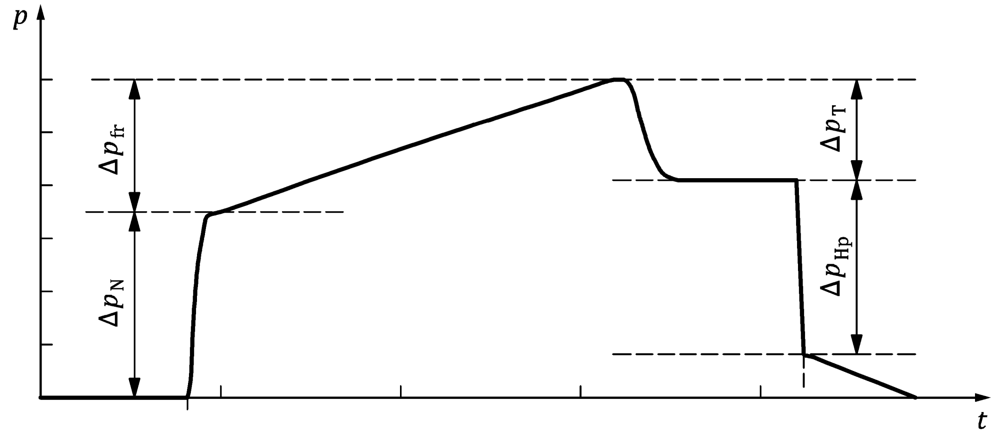


Figure 7 — Train-tunnel -pressure signature at a fixed position in a tunnel (detail)

The train-tunnel pressure signature (Δp_N, Δp_{fr}, Δp_T and Δp_{HP}) can be derived from calculations or measurements at a fixed position in a tunnel.

The following methods are suitable for characterizing the aerodynamic quality of a train in a tunnel.

7.2.2 Full-scale measurements at fixed locations in a tunnel

7.2.2.1 Test site

The tunnel shall have a constant cross-section and no side passages or airshafts over a minimum tunnel length given by:

$$L_{\text{tu,min}} = x_p + \frac{cL_{\text{tr}}}{2v_{\text{tr}}} + \Delta L_1 \text{ , with } v_{\text{tr}} = v_{\text{tr,test}} \left(\text{in m} / s\right) \text{, if } \Delta p_{\text{HP}} \text{ is needed} \tag{2}$$

where the additional length ΔL_1 ensures a good temporal separation of the individual pressure variations and ideally should be about 150 m.

Deviations in cross-sectional area shall be considered in a later stage of assessment. Air shafts shall not have any effect, i.e. plain tunnels should be used or any air shafts present shall be blocked during tests.

Tunnel cross-sectional area and altitude changes are not limited for the test.

Tunnels should have a steep angled or plain portal. Tunnels with hoods should be avoided, or corrections shall be applied for their effect.

For the tunnel near the entry portal and the test section, the cross-section shall be determined. The value of the cross-sectional area may be rounded to the nearest 0,25 m². A possible way to do so is based on technical drawings. The characteristic main dimensions (height and width) shall be measured at site and documented.

7.2.2.2 Measurement positions

In order to obtain precise values of Δp_{N}, Δp_{fr}, Δp_{T} and Δp_{HP} for a fully developed wave pattern, it is necessary to ensure the following condition on the measurement position in the tunnel. The distance, x_{p}, between the entrance portal and the measuring position shall be:

$$x_p = \frac{cL_{\text{tr}}}{c - v_{\text{tr}}} + \Delta x_1 \tag{3}$$

where

c = 340 m/s.

The additional distance Δx_1 ensures a good temporal separation of the individual pressure variations. Δx_1 shall be between 100 m and 300 m. The measuring system shall be installed at x_{p} to avoid wave damping effects.

7.2.2.3 Test train requirements

For fixed or pre-defined train compositions consisting of more than one train unit, it is sufficient to assess a train composition consisting of at least two units and of a minimum length of 120 m.

For single rolling stock units fitted with a driver's cab, conformity shall be assessed for units at the front and rear of a rake of passenger carriages of at least 100 m in length. Tests shall be carried out with either one unit, or with two identical units; one at the front and one at the rear of the train. The carriages should be comprised of those likely to be used in operational conditions.

Conformity of other rolling stock, see 5.1.2.4, shall be assessed by a rake of the vehicles to be checked with a minimum length of 100 m. The rake shall consist of units of the same type. Tests shall be carried out with two units fitted with driver's cabs; one at the front and one at the rear of the train. The units fitted with driver's cabs should be comprised of those likely to be used in operational conditions.

If the train length used for assessment is not compliant with the reference case, the results shall be corrected according to 7.3.

7.2.2.4 Train speed requirements

The selected nominal test speed $v_{\mathrm{tr,test}}$ of the train nose entering the tunnel shall not be less than 80 % of the reference speed, according to Table 2. The nominal test speed should be equal or above the reference speed.

For a valid set of measurements, at least 50 % of the measurements shall be taken within ± 5 %, and 100 % of the measurements within ± 10 % of the nominal test speed $v_{\mathrm{tr,test}}$.

The difference between the measured speeds of the first and last axle shall not exceed 3 % of the speed of the first axle.

7.2.3 Instrumentation

7.2.3.1 General

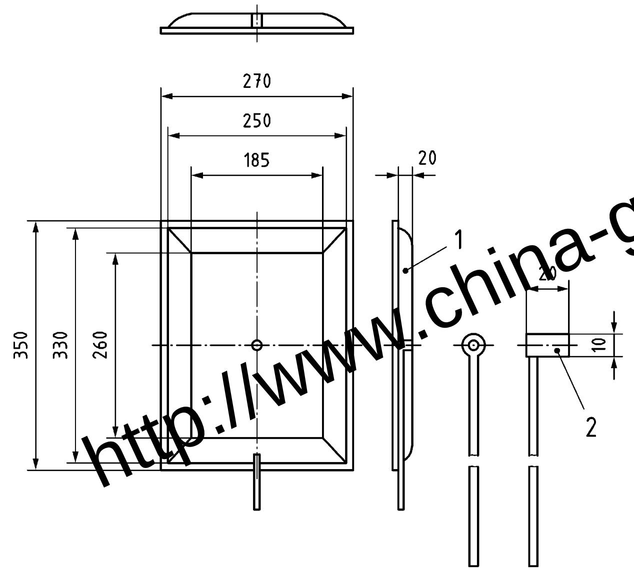
Pressures are measured at one position along the tunnel only using pressure transducers. It is recommended to place the pressure measurement at a location at which the flow field is undisturbed by tunnel installations. It is recommended to estimate the likely pressure signal range when planning the testing. The pressure transducers shall be calibrated prior to use over 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 $\Delta p_{\mathrm{N}} + \Delta p_{\mathrm{fr}}$.

NOTE The data acquisition system includes signal conditioning, signal transmission and recording/sampling of data.

The measurement of static pressure shall be made in such a way as to ensure that air flow in the tunnel does not affect the measurement. A suitable realization of such an installation is by using a flat mounting board with pressure taps set in it. The mounting board shall be mounted on the tunnel wall, and should be as thin as possible. An example is shown in Figure 8. Another suitable set-up is by mounting a static (or static Pitot) tube aligned parallel to the tunnel axis. The static pressure is in this case measured at the static pressure port of the tube.

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.

Dimensions in millimetres



Key

1 smooth plate
2 pressure tapping

Figure 8 — Example of schematic description of set up for pressure measurement

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). Pressure changes in the tunnel act on the tubes connected to the pressure reservoir and may affect the reference pressure. 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.

Ambient pressure, temperature and humidity measurement equipment shall be placed inside the tunnel within about 50 m from the tunnel portal. The air speed sensor shall be placed either near the pressure measurement position or within 50 m from the tunnel portal. The air speed sensor should be positioned such that is not significantly affected by boundary layer effects. Therefore, it should be placed at a distance of at least 0,8 m from any tunnel surface, if possible. The uncertainty in the air speed measurement shall be determined and shall not exceed ± 0,3 m/s for an air speed of 6 m/s. The sensor shall be capable of distinguishing between flow directions. Acquisition of temperature and humidity shall comply with ISO 8756.

The actual test train speed $v_{\mathrm{tr,test},i}$ of each run shall be measured close to the tunnel portal within ± 50 m from the portal for the first and the last axle of the train with a precision of 1 %. This can be realized by two light barriers or axle detection devices in the track. As an alternative to detecting the axles, the speed of nose and tail may be measured by appropriate sensors. Both train speeds shall be documented. If Δp_{HP} is to be measured, an additional train speed measurement shall be made at the measuring position x_{p}.

The layout of the chosen test site shall be recorded. This shall include a description of the location including the portal, the evolution of tunnel cross-sectional area with the distance from the portal and the position of equipment.

Correct identification and recording of the passing train type, its speed, length and composition are mandatory (e.g. by video or by recording the axles pattern).

7.2.3.2 Data acquisition system

The pressure signal shall be sampled at a minimum of 300 Hz with anti-aliasing filters with a cut-off frequency of at most one quarter of the sampling rate. If no analogue filters are used, digital filtering is allowed if sufficiently higher sampling rates are used. Air speed in the tunnel shall be recorded with a sampling rate of at least 1 Hz. Sampling of train speed shall be chosen to ensure the precision requirement. The time period of measurements shall start at least 60 s before the train enters the tunnel portal and last until at least 10 s after the train tail passing x_p. It is recommended to extend the measurement to about 120 s after the train tail passing x_p.

Temperature and humidity measurements shall ensure a reading within ± 5 minutes after the train entering the tunnel.

7.2.4 Full-scale measurements on the exterior of the train

If it is not possible to carry out measurements at fixed locations in a tunnel, Δp_N, Δp_{fr} and Δp_T can be approximated by measurements of $\Delta p_{N,o}$, $\Delta p_{fr,o}$ and $\Delta p_{T,o}$ on the exterior of the train, see Figure 9. 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 air flow in the tunnel. However, if there is, its influence on the measurements shall be checked.

Pressures are measured using transducers on the exterior of the train. These shall be calibrated prior to use over the expected pressure range, typically ± 4 kPa. The measurement error of the pressure transducer including the data acquisition system shall be less or equal than 2 % of the expected value for $\Delta p_N + \Delta p_{fr}$.

To get the complete frictional pressure rise, Δp_{fr}, it is necessary to measure the pressures on the outside of the train at position x_1 just behind the nose at the position where the full cross-sectional area is reached. Instrumentation according to 7.2.3 is recommended for the external pressure.

The speed of the train shall be determined with a precision of 1 % and shall be constant during the entry into the tunnel to within 3 %.

Data shall be sampled at a rate of at least 5 v_{tr}/L_n Hz, with anti-aliasing filters applied having a cut-off frequency of at most one quarter of the sampling rate. If no analogue filters are used, pure digital filtering is allowed, if sufficiently higher sampling rates are used.

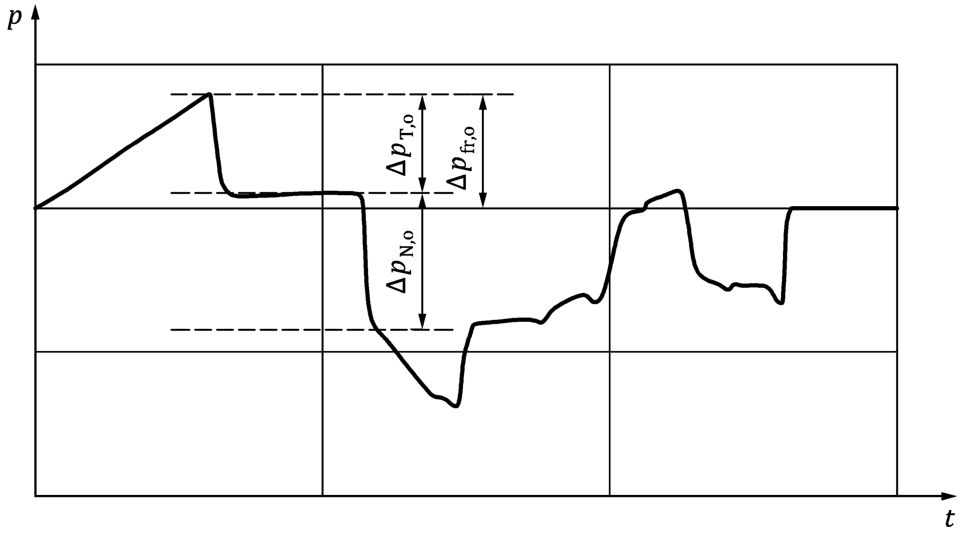


Figure 9 — Train-tunnel-pressure signature on the nose of the train

The minimum tunnel length $L_{\text{tu,min}}$ is:

$$L_{\text{tu,min}} = \frac{L_{\text{tr}}}{2}\frac{c}{v_{\text{tr}}}\left(\frac{c+v_{\text{tr}}}{c-v_{\text{tr}}}\right)+\Delta L_2 \text{ , with } v_{\text{tr}} = v_{\text{tr,test}} \tag{4}$$

where the additional length ΔL_2 ensures a good temporal separation of the individual pressure variations, and ideally should be about 200 m.

As the tunnel length reduces the amplitude of the first reflection of the nose wave $\Delta p_{\text{N,o}}$ by friction, the tunnel should not be much longer than $L_{\text{tu,min}}$.

7.2.5 Predictive formulae

Estimates for Δp_{N}, Δp_{fr}, Δp_{T} and Δp_{HP} can be made using the formulae given in Annex A, A.2, A.3 and A.4. For tunnels with varying cross-sectional area, the smallest area shall be considered.

The maximum pressure change (peak-to-peak) $\Delta p_{\max}$ under the worst-case conditions, (e.g. critical tunnel length, critical crossing or parallel running, critical location), are given by the following formulae.

At a fixed location in a tunnel for two identical trains crossing or running in a parallel:

$$\Delta p_{\max} = 2\Delta p_{\text{N}} + 2\Delta p_{\text{fr}} + 2\Delta p_{\text{T}} + 2\Delta p_{\text{HP}} \tag{5}$$

At a fixed location in a tunnel for a 1 train situation:

$$\Delta p_{\max} = \Delta p_{\text{N}} + \Delta p_{\text{fr}} + \Delta p_{\text{T}} + \Delta p_{\text{HP}} \tag{6}$$

On-board a train in a situation with two identical trains crossing:

$$\Delta p_{\max} = 2\Delta p_{\text{N}} + 2\Delta p_{\text{fr}} + 2\Delta p_{\text{T}} + 2\Delta p_{\text{HP}} + 2\Delta p_{\text{alt}} \tag{7}$$

On-board a train in a single train situation:

$$\Delta p_{\max} = \Delta p_{\text{N}} + \Delta p_{\text{fr}} + \Delta p_{\text{T}} + \Delta p_{\text{alt}} \tag{8}$$

where

$$\Delta p_{\text{alt}} = -g\rho_0\Delta h \tag{9}$$

is the natural pressure variation due to the difference in altitude;

where

ρ_0 = 1,225 kg/m^3

Δh is the difference between maximum and minimum altitudes in the tunnel (m).

7.2.6 Assessment by numerical simulation

As three-dimensional effects are limited to the entrance region of a tunnel and nose and tail of a train, the propagation of pressure waves in tunnel can be modelled accurately by one dimensional (1-D) computational models. Such models are in widespread use. The models are based on following parameters:

— Characteristics of tunnel: cross-sections and perimeters of tube and shafts, friction coefficient, portal losses, lengths, air temperature and ambient pressure, density, altitude.

— Characteristics of trains: cross-sections and perimeters of trains, friction coefficient, head and tail pressure losses, lengths.

— Characteristics of operation: train speed profile, tunnel entry time, direction of travel.

The following correlation, based on Figure 4, is considered a suitable approximation for the train perimeter, Pe_{tr}, if only the train area is known.

$$Pe_{tr} = 3,139 \cdot S_{tr}{}^{0,5493} \tag{10}$$

The following correlation is considered a suitable approximation for the tunnel perimeter, Pe_{tu}, if only the tunnel area is known.

$$Pe_{tu} = \left(2+\pi\right)\left(\frac{2 \cdot S_{tu}}{\pi}\right)^{0.5} \tag{11}$$

The outputs of the models are time series of pressure and air speed at defined locations in the tunnel or along the train.

Physical effects should include generation of pressure variations due to entry, passage and exit of trains in tunnels, propagation of pressure waves through the tunnel accounting for friction effects, (partial) reflections at cross-sectional changes and at the portals of the tunnel, shafts if included and trains in the tunnel. Parameters are assumed to vary along the tunnel, but are constant at each cross-section.

Pressures and air speeds are assumed to vary in time. Calculations shall be made with validated numerical methods. Signal filtering is usually not applied to simulated signals, as it may result in overshooting amplitudes due to filter characteristics.

More specific tools may be necessary to investigate micro-pressure waves (for generation, steepening and emission), see Annex C.

7.2.7 Reduced scale measurements at fixed locations in a tunnel

Models of the test train shall be constructed which accurately represent the train nose and tail (tolerance of 10 mm full-scale maximum deviation from the original shape of the vehicle body), and have a good representation of the bogies, intercar gaps and train exterior surface features (e.g. roughness, shape). The test models shall be at a scale of 1/25 or larger for the test train to ensure that Reynolds number effects are minimized. The full-scale train Mach number shall be respected.

With scaled tunnel and train models, the pressure waves in the tunnel will reproduce those at full-scale, except that the time base will be decreased by model scale. For instance, in a 1/25 scale test, all the pressure waves will occur on a time base 25 times faster than at full-scale.

In most cases it is not practicable to use models which represent the full-scale train length. A train model consisting of the leading and end cars, with two intermediate coaches is a minimum for this purpose. The frictional part of the pressure signature for these reduced length models reproduces the full pressure rise, if the full-scale length is accounted for by extrapolation. The use of shorter train models will produce conservative values for Δp_{T} and Δp_{HP}.

The tunnel model shall be rigid and very well sealed onto the test rig bed to ensure that no reduction of pressure wave amplitude occurs. Sealing tests of the tunnel mounting onto the test bed shall be undertaken to check the tunnel leakage value. The full-scale equivalent leakage area shall be $1\mathrm{x}10^{-3}$ m^2/m or less.

The minimum tunnel length and measurement position shall respect the dimensions given in 7.2.2.

Pressures are measured using transducers in the tunnel. These shall be calibrated prior to use over the expected pressure range, typically ± 4 kPa. The measurement error shall be less than 1 %.

The speed of the train shall be known with a precision of 1 % and should be constant during the entry into the tunnel within 3 %.

Data shall be sampled at a rate of at least 5 $v_{\mathrm{tr}}/L_{\mathrm{n,model}}$ Hz, with anti-aliasing filters with a cut-off frequency of at most one quarter of the sampling rate. If no analogue filters are used, pure digital filtering is allowed if sufficiently higher sampling rates are used.

7.3 Assessment of maximum pressure changes (vehicle reference case)

7.3.1 General

The assessment is performed based on full-scale measurements with the investigated train according to 7.2.2. The number of test runs shall be as in the requirements stated in 7.3.6. Further assessment and correction of the measurement data are necessary to compare to the reference case in 5.1.2.1. Three alternative approaches to transform the measurement data are described in 7.3.2, 7.3.3 and 7.3.4. A general assessment of the pressure time history is provided in 7.3.5. The outcome of the transformation is compared to the reference case according to 7.3.6.

NOTE All three approaches are considered to be suitable. No recommendation is given regarding the choice. An application example showed differences of ± 5 % in $\Delta p_{\mathrm{N}} + \Delta p_{\mathrm{fr}} + \Delta p_{\mathrm{T}}$.

7.3.2 Transformation of measurement values by a factor (approach 1)

The signal of measured pressures $p_{(t)}$ is multiplied by the factor $\frac{k_2}{k_1}$ to correct for blockage, train speed and air flow in the tunnel.

$$k_j = \rho_j \cdot v_{tr,j}^2 \left(\frac{1}{\left(1 - B_j\right)^2} - 1 \right) \tag{12}$$

with

$$\rho_j = \frac{p_{\mathrm{atm}} - H_j \cdot 0{,}378 \cdot \exp\left(\frac{17{,}51 \cdot \theta_j}{241 + \theta_j} + 1{,}814 \right)}{287{,}05 \cdot \left(273{,}15 + \theta_j\right)} \quad j = 1, 2 \tag{13}$$

$$v_{tr,1,rel} = v_{tr,test} + u_0 \tag{14}$$

and

Index j = 1 represents the situation as measured in the test;

Index j = 2 represents the reference scenario;

H	is the relative humidity (%);
ρ_2	is set to an air density of 1,225 kg/m^3;
$v_{\mathrm{tr,test}}$	is the train speed during the test (m/s);
u_0	is the measured air flow at the moment of tunnel entry, (positive in the direction opposed to the train) (m/s);
p_{atm}	is the ambient atmospheric pressure during the test (Pa).

NOTE The density formula is adopted from EN 61400-12-1:2017

If the train length is not compliant with the reference case, linear extrapolation of Δp_{fr} with the tested train length shall be performed, taking into account any couplings between train units. The pressure changes Δp_{N}, Δp_{fr} and Δp_{T} shall be derived for the reference case using the method in 7.3.5 and compared to the reference case according to 7.3.6.

7.3.3 Transformation of measurement values based on A.3.3 (approach 2)

For each measured signal, the pressure changes are derived according to 7.3.5 resulting in a table.

To derive a corrected Δp_{N}, the value of ζ_{h0} is set to zero in Formula (A.10). Then Formulae (A.9), (A.10) and (A.11) from A.3.3 are solved to derive ζ_{h}, which is applied to the reference case to compute a corrected Δp_{N}.

To derive a corrected Δp_{fr}, the Formulae (A.12), (A.13) and (A.14) from A.3.4 and Formula (15) and (16) are solved first to derive the train roughness parameter k_{s}. An assumption on tunnel friction $C_{\mathrm{f,tu}}$ is needed and may be set to 0,005. This value represents a tunnel with smooth walls e.g. modern concrete lined, ballast and track, and is a conservative value for tunnels having rough walls. Also for Formula (A.12), an assumption is needed for $C_{\mathrm{f,tr}}$. This is given by:

$$C_{\mathrm{f,tr}} = 0,25 \cdot \left(2 \cdot log_{10} \left(\frac{D_{\mathrm{h}}}{k_{\mathrm{s}}} \right) + 1,14 \right)^{-2} \tag{15}$$

with

$$D_{\mathrm{h}} = 4 \cdot \left(\frac{S_{\mathrm{tu}} - S_{\mathrm{tr}}}{Pe_{\mathrm{tu}} + Pe_{\mathrm{tr}}} \right) \tag{16}$$

The parameter k_{s} is derived from the formulae stated above from the test results and applied to the reference case as a constant value, to compute a corrected Δp_{fr}.

As D_{h} is different for the test and reference conditions, the formulae shall be solved first for the test condition and then for the reference case, using the train length as defined in 5.1.2.

To derive a corrected Δp_{T}, the value of ζ_{t0} is set to zero in Formula (A.17). Then Formulae (A.15), (A.16), (A.17), (A.18) and (A.19) from A.3.5 are solved to derive ζ_{t} from (A.16). The value of ζ_{t1} is derived from Formula (A.17) and applied as a constant to the reference case to compute a corrected Δp_{T}. The air density in the reference case is set to $\rho_{\mathrm{amb}} = 1{,}225\ \mathrm{kg/m^3}$.

NOTE The background to this approach is found in [2], [11] and [12].

The derived pressure changes Δp_{N}, Δp_{fr} and Δp_{T} shall be compared to the reference case according to 7.3.6. If the train length is not compliant with the reference case, linear extrapolation of Δp_{fr} with the tested train length shall be performed taking into account any couplings between train units.

7.3.4 Transformation by simulation (approach 3)

In addition to the previous approaches in 7.3.2 and 7.3.3, simulation tools represent an alternative method to convert the measured pressure signals to the reference case.

The track test conditions can differ from the ones defined for the reference case and, thus, the first step of the process involves a comparison between the pressure measurements from the tests and the simulations, to ensure that the simulations are able to predict the measurements to a satisfactory accuracy.

The steps for comparison are as follows:

- the available train and tunnel data with regard to the track tests shall be used as input parameters to the simulation software to define the assessment case scenario;

- the tunnel friction coefficient $C_{\mathrm{f,tu}}$ is required, this may be obtained from tests, by previous knowledge or may be unknown;
  - a suitable choice of $C_{\mathrm{f,tu}} = 0{,}005$ may be taken if the friction coefficient is unknown. It represents a tunnel with smooth walls e.g. modern concrete lined, ballast and track and is a conservative value for tunnels with rough walls;
- the obtained pressure signal $p(t)_{\mathrm{sim}}$ from the simulation software shall be compared to the signal $p(t)_{\mathrm{test}}$ from the track test.

The comparison of the signals shall involve:

- a graphical comparison of $p(t)_{\mathrm{sim}}$ and $p(t)_{\mathrm{test}}$. The simulation should visually reproduce the overall characteristics and pressure changes of the measurements;
- applying the assessment of the pressure time history in 7.3.5 to measurements and simulations;
- a numerical comparison of the pressure changes Δp_{N}, $(\Delta p_{\mathrm{N}} + \Delta p_{\mathrm{fr}})$ and $(\Delta p_{\mathrm{N}} + \Delta p_{\mathrm{fr}} + \Delta p_{\mathrm{T}})$ where:

$$\varepsilon_{\Delta pN} = \left| \frac{\Delta p_{\mathrm{N,test}} - \Delta p_{\mathrm{N,sim}}}{\Delta p_{\mathrm{N,test}}} \right| \leq 0{,}1;$$

$$\varepsilon_{\Delta p_{(\mathrm{N+fr})}} = \left| \frac{\Delta p_{(\mathrm{N+fr}),\mathrm{test}} - \Delta p_{(\mathrm{N+fr}),\mathrm{sim}}}{\Delta p_{(\mathrm{N+fr}),\mathrm{test}}} \right| \leq 0{,}05;$$

$$\varepsilon_{\Delta p_{(\mathrm{N+fr+T})}} = \left| \frac{\Delta p_{(\mathrm{N+fr+T}),\mathrm{test}} - \Delta p_{(\mathrm{N+fr+T}),\mathrm{sim}}}{\Delta p_{(\mathrm{N+fr+T}),\mathrm{test}}} \right| \leq 0{,}05;$$

- from this comparison ζ_{h}, $C_{\mathrm{f,tr}}$ and ζ_{t} coefficients are derived from the input values used in the simulation tool;
- using the obtained coefficients, converted as necessary for the reference tunnel dimensions, the reference case shall be simulated with the air density of $\rho_{\mathrm{amb}} = 1{,}225\ \mathrm{kg/m^3}$ and $C_{\mathrm{f,tu}} = 0{,}005$ with the train length according to 5.1.2.

The pressure changes Δp_{N}, Δp_{fr} and Δp_{T} shall be derived for the reference case using the assessment in 7.3.5 and compared to the reference case according to 7.3.6.

7.3.5 Assessment of the pressure time history

The following procedure can be used to extract the properties of the tunnel pressure signature from a measured pressure history:

a) The recorded pressure history should be roughly cut to the region of interest. Useful markers to identify the region of interest are the pulses recorded to measure the train speed, the positions of the maximum and minimum of the signal and positions of large signal gradients.

b) For the procedure to run stably the signal should not contain high frequency noise. Therefore, the measured signals should be low-pass filtered using an appropriate filter with a cut-off frequency of 10 Hz and negligible phase shift. Simulated signals should not be filtered.

c) The offset in the signal should be determined properly by computing the mean value of the signal before the beginning of the first rise Δp_{N} of the signal. The averaging interval should be restricted to a suitable range of e.g. 30 s before the first pressure rise. It is recommended to iteratively adjust the position of the averaging interval such that the first pressure rise is consistently excluded from the averaging, but the offset is still representative of the signal just before the first pressure rise.

   1) If residual pressure waves persist in the signal, the length of the averaging interval should be a whole multiple of the period of the residual signal.

   2) The standard deviation, σ, or the peak-to-peak value of the filtered signal within the averaging interval can be used as a measure to assess the magnitude of residual waves.

d) The horizontal line 1 can be drawn at the offset level, p_{offset}, see Figure 10. Alternatively, the offset can be subtracted from the signal before further processing.

e) It is recommended to limit the pressure signature to a region of interest as displayed in Figure 10.

f) Point C in Figure 10 is the maximum of the signal within the region of interest.

g) The gradient of the filtered signal in the region of the first pressure rise Δp_{N} is computed and the maximum positive gradient and its location are determined. Point A marks the location of the maximum gradient. Line 2 is drawn through point A. The slope of line 2 equals the gradient of the filtered signal at point A.

h) Line 3 is drawn through points C and B. Point B is defined as the first point after point A, where line 3 becomes tangential to the filtered signal.

   1) Point B can be found iteratively starting at point A and comparing the slope of the resulting line through point C with the local forward gradient at the chosen point. Point B is found when the local forward gradient becomes smaller than the slope of the resulting line through point C the first time, see Figure 11. The local forward gradient at point B shall not be negative.

   2) The location of point B should be checked visually to ensure that it characterizes the nose pressure rise. Typically point B should be found within $(t_{\mathrm{B}} - t_{\mathrm{A}}) \leq (60/v_{\mathrm{tr,test}})$ seconds after point A. If point B is not found close enough after point A to still characterize the nose pressure rise, the described method might not be suitable to analyse that particular case, e.g. when analysing short trains. In this case, another method such as that described below in (m) to (o) and illustrated in Figure 12 should be applied, or the above conditions should be adjusted. The time t_{A} denotes the time of point A. The times t_{B}, t_{S}, t_{T} are defined in the same way for points B, S, T, as well as the pressures p_{B}, p_{S}, p_{T}.

NOTE The value of 60 m in the formula for the time interval given above, allows for the effect of portal design.

i) Point D is located at the intersection of lines 2 and 3.

j) The pressure rises, Δp_{N} and Δp_{fr}, can be determined from the pressure level at point D considering the signal offset p_{offset} and the difference in pressure levels between points C and D respectively.

k) For further assessment, data beyond point E shall be neglected. Point E is defined as the position in the signal where line 4 becomes tangential to the filtered signal with line 4 running through point C. Point E can be identified using a procedure as described for locating point B.

l) Point F is the minimum of the measured signal between points C and E, and the tail pressure drop Δp_{T} can be determined from the difference in pressure levels between points C and F.

1) In some cases, the low-pass filtering generates some signal undershoot (compared with the unfiltered signal) in the time interval between points C and E, whereby Δp_T is exaggerated. If this is observed, point F should be determined from the unfiltered signal or filtered data applying a higher cut-off frequency. Points A to E should not be re-analysed in this case.

Alternatively, the nose pressure rise Δp_N can be determined from the low-pass filtered signal, as illustrated in Figure 12:

m) The region of interest is restricted to data up to point C in Figure 10.

n) Point S is chosen where the low-pass filtered data equals the offset level the last time, see detail in Figure 12.

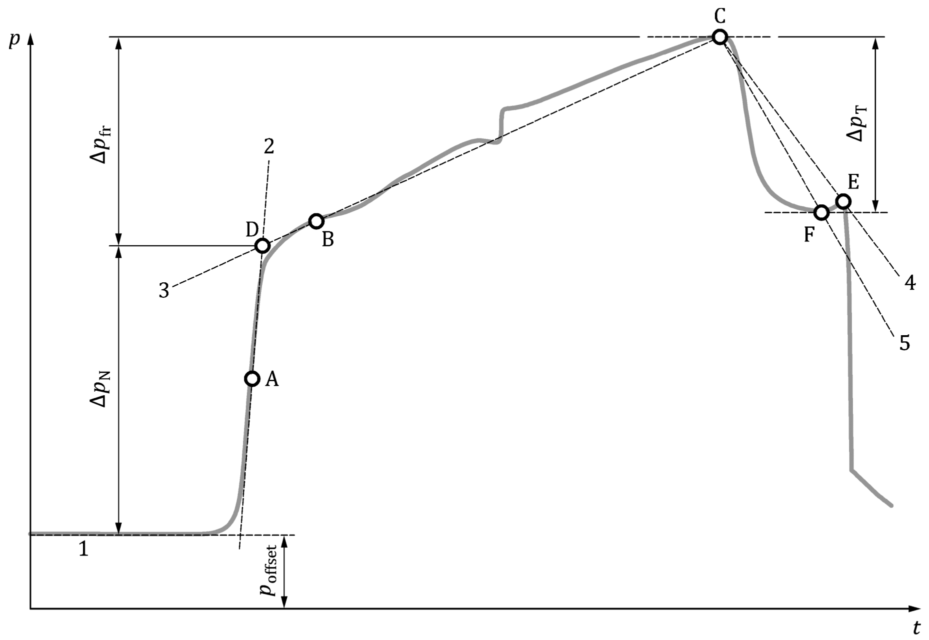
o) Point T can be determined iteratively:

   1) For each choice of t_T, with $t_T > t_S$, a time $t_{50\,\%}$ can be determined where the signal corresponds to 50 % of the value at the time t_T: $p\left(t_{50\%}\right) - p_{\text{offset}} = 0{,}5 \cdot \left(p\left(t_T\right) - p_{\text{offset}}\right)$

   2) The areas A_S and A_T can be computed by numerical integration of the filtered signal between instants t_S, $t_{50\,\%}$ and t_T. For high accuracy it is recommended to use trapezoidal integration and linear interpolation of the filtered signal to match the instants exactly.

   3) The difference between areas A_S and A_T is computed and t_T is varied to minimize this area difference using a suitable algorithm such as Newton's method.

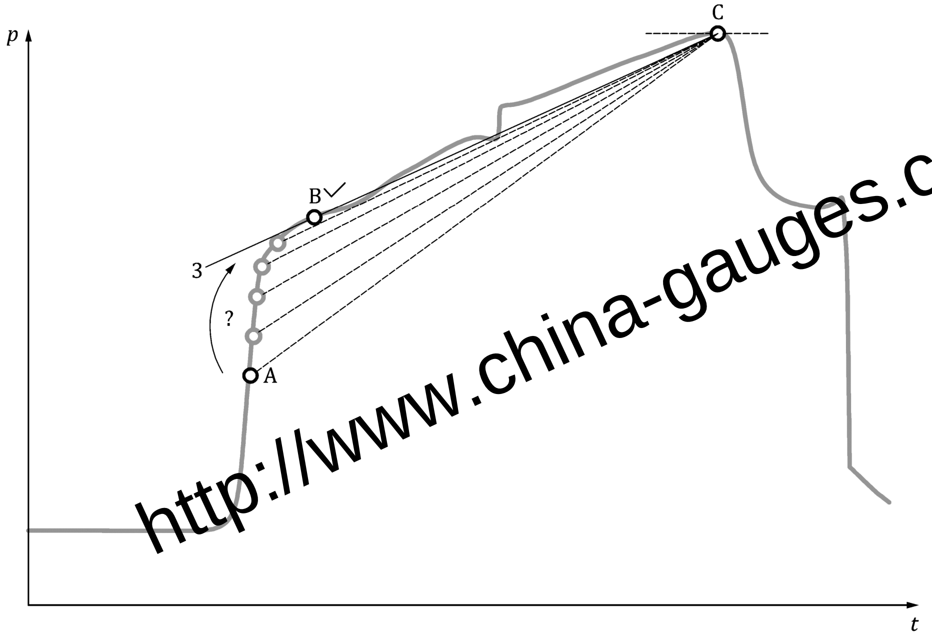
The above procedure may also be modified and used as an alternative to assess Δp_T.



Key

— measured signal

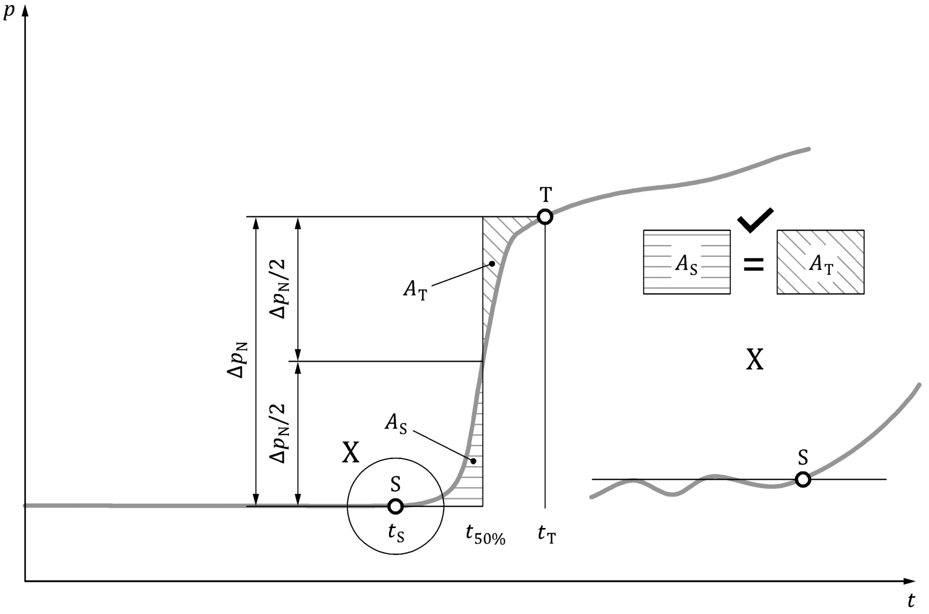
Figure 10 — Properties of measured the train-tunnel -pressure signature signal



Key

▬ measured signal

Figure 11 — Searching for point B iteratively



Key

▬ measured signal

Figure 12 — Alternative determination of ΔpN

7.3.6 Assessment quantities and comparison

The test measurements need to be checked to ensure that there was no other train in the tunnel during the test, and that no residual pressure waves remained in the tunnel. Also, there should be no initial air flow in the tunnel. However, if any of these conditions exist, the test sample shall be eliminated or corrected. Evidence and documentation shall be provided.

Ideally, at least five independent and comparable test samples are required and a minimum of three samples shall be obtained. The assessment quantities are the average pressure changes, $\overline{\Delta p_{\mathrm{N}}}$, $\overline{\Delta p_{\mathrm{fr}}}$, or $\overline{\Delta p_{\mathrm{T}}}$. These values shall be compared to the reference case according to Table 2.

When assessing the conformity of single rolling stock units fitted with a driver's cab, Δp_{fr} is set to 1 250 Pa (for trains with $v_{\mathrm{tr,max}} < 250$ km/h) or to 1 400 Pa (for trains with $v_{\mathrm{tr,max}} \geq 250$ km/h).

When assessing the conformity of other passenger rolling stock according to 5.1.2.4, then Δp_{N} is set to 1 750 Pa and Δp_{T} to 700 Pa (for trains with $v_{\mathrm{tr,max}} \leq 230$ km/h) or to 1 600 Pa and 1 100 Pa (for trains with $v_{\mathrm{tr,max}} > 230$ km/h).

7.4 Assessment of maximum pressure changes (infrastructure reference case)

7.4.1 General

The Infrastructure assessment is performed by calculating the maximum pressure changes for a reference train running at the maximum design speed in the tunnel. This maximum pressure variation shall not exceed 10 kPa. Compliance shall be made for a single reference train running in a single track tunnel, or for a crossing of two reference trains in a double-track tunnel; (in which the worst case crossing scenario shall be considered).

Infrastructure assessments for tunnels with maximum line speeds below 200 km/h are limited to the assessment of a reference train with 200 km/h maximum design speed.

It is not necessary to assess other vehicle characteristics.

7.4.2 Assessment method

For this assessment, the following steps shall be undertaken:

a) Determine the train input parameters to be used in the process (i.e. reference train definition). This reference train is defined by the limit values of the pressure signature given in Table 2. Depending on the design speed in the tunnel, the appropriate reference case shall be chosen. These parameters shall be appropriate to the method used to calculate the maximum pressure, (see the methods described in 7.2.5 and 7.2.6, i.e. predictive formulae or simulations). Using the standard tunnel parameters, a pressure time history shall be computed and documented in a diagram similar to Figure 7.

   Train parameters include:

   — Cross-sectional area (see 6.1.2);

   — Lengths equal to 200 m and 400 m (see 6.1.2);

   — Friction coefficient, nose and tail losses (worst case values to be derived from Table 2).

The following tunnel parameters shall be used for this step:

- Atmospheric pressure p_{atm} = 101 325 Pa, θ = 15 °C, air density ρ_{amb} = 1,225 kg/m^3;
- Tunnel cross-sectional area (defined by the reference scenarios in Table 2);
- Tunnel length; sufficient to have a complete signature (see 7.2.2.1);
- An assumption about tunnel friction: $C_{\mathrm{f,tu}}$ should be set to 0,005;
- Portal losses.

b) Define the input parameters of the real tunnel being considered: cross-sectional area, length, entry shape/portal, friction coefficient, altitude variation, shafts, cross-sectional area changes and any construction features (see Table 9 for relevant features).

c) Justification of the use of the tunnel parameters (friction coefficient, portal losses, etc.) shall be provided, where possible by the use of the experimental data (pressure time histories obtained in a test or in a similar tunnel).

d) Determination of maximum pressure in single track tunnels.

Using the train and tunnel parameters defined in the previous steps, compute the maximum pressure change (peak-to-peak), Δp_{max}, on the outside of the train for a single reference train running at the maximum design speed in the tunnel with 1-D simulations (see 7.2.6) or predictive formula (see 7.2.5, Formula (8)). 1-D simulations shall be performed for the three sensor positions x_1, x_2 and x_3 defined in 7.7.3.4.

e) Determination of maximum pressure in double track tunnels.

With the train and tunnel parameters defined in the previous steps, compute Δp_{max} for a critical crossing of two reference trains at the maximum design speed in the tunnel. The crossing of two 200 m trains and two 400 m trains shall be considered. The computations shall be performed for the three sensor positions x_1, x_2 and x_3 defined in 7.7.3.4 for the variation of relative entry times t_{e} as defined in 7.7.3.4. To include the worst case scenario, the maximum pressure change (peak-to-peak) Δp_{max} on the outside of the train shall be derived from all of the simulations. As an alternative to using simulations, the predictive formula for two trains crossing may be applied (see 7.2.5, Formula (7)) ignoring Δp_{alt}.

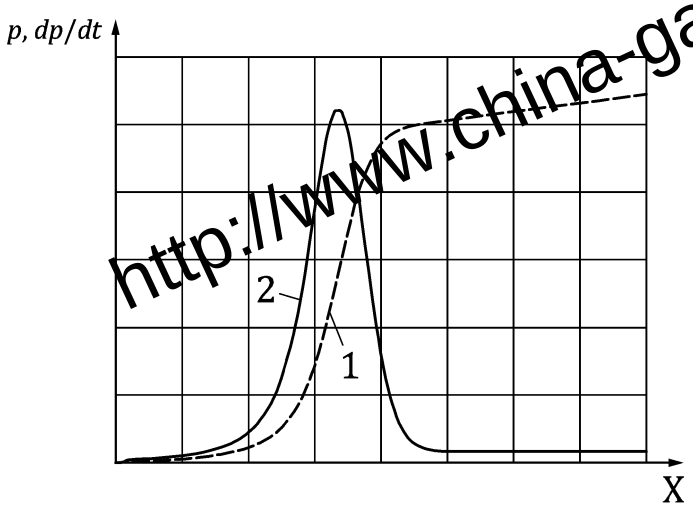
If, for a given tunnel design, the criteria are not met, one or more of the train design speed, the tunnel area, the tunnel length, shafts or portals will need to be modified.

All relevant parameters and calculation results shall be documented.

7.5 Assessment of the pressure gradient of a train entering a tunnel (vehicle reference case, with respect to micro-pressure wave generation)

7.5.1 General

The limiting criterion is the maximum gradient (dp/dt) of the entry pressure wave. In Figure 13 there is an example of a train-tunnel entry compression wave measured inside a tunnel shown for visualization.



Key

1 *p*
2 dp/dt
X time

Figure 13 — Example of an entry compression wave

7.5.2 Assessment by simulations

For a rolling stock assessment using CFD simulations, the following steps shall be undertaken according to 7.6:

a) simulate tunnel pressures during entry of the reference vehicle with a speed of 250 km/h into the reference tunnel,

b) show that, in this case, the maximum entry pressure gradient, dp/dt, is in the range [8 800 Pa/s, 9 500 Pa/s] to validate the simulation settings,

c) using the same settings, simulate entry of the assessed vehicle in the reference tunnel with a speed of 250 km/h, or with the maximum design speed if it is lower than 250 km/h,

d) compare the maximum entry pressure gradient of the assessed vehicle with the results of the reference vehicle,

e) the assessed vehicle passes if its maximum pressure gradient is not higher than one of the reference vehicle simulation.

NOTE 1 Steps a) and b) demonstrate the quality of the assessment.

NOTE 2 As steps c), d) and e) indicate that trains running at speeds below 250 km/h may have bluffer nose shapes than the reference train, but still produce the same maximum pressure gradient as the reference vehicle at 250 km/h.

7.5.3 Assessment by moving model rig tests

For a rolling stock assessment using moving model rig tests, the following steps shall be undertaken according to 7.6.3:

a) measure tunnel pressures during the entry of the reference vehicle into the reference tunnel with a speed of 250 km/h,

b) measure tunnel pressures during the entry of the assessed vehicle into the reference tunnel with a speed of 250 km/h or with the maximum design speed if it is lower,

c) compare the maximum entry pressure gradient with the results of the reference vehicle,

d) the assessed vehicle passes if the maximum value of dp/dt is not higher than for the reference vehicle.

Evidence and documentation on the quality and repeatability of the test shall be provided by comparing the maximum entry pressure gradient to those obtained by other laboratories for the reference case or to a full scale test.

7.6 Assessment of the micro-pressure wave (infrastructure reference case)

7.6.1 General

For an infrastructure assessment, the following steps shall be undertaken according to 7.6.2 as the basis for a prediction of micro-pressure wave emissions in conjunction with compression wave propagation and micro-pressure wave emission by simulations:

a) simulate the pressures during the entry of the reference vehicle in the reference tunnel at a speed of 250 km/h,

b) show that, in this case, the maximum entry pressure gradient dp/dt is in the range [8 800 Pa/s, 9 500 Pa/s],

c) simulate the pressures during the entry of the reference vehicle in the assessed tunnel at a speed of 250 km/h or with maximum portal entry speed if it is higher using the same setup,

d) use the obtained entry pressure wave to calculate the micro-pressure wave emissions,

e) compare the micro-pressure wave emissions with limit values and apply countermeasures if needed.

Use 250 km/h in step c) even if maximum portal entry speed is lower to account for bluffer nose shapes than the reference train.

Alternatively, by using moving model rig tests according to 7.6.3:

f) measure the pressures during the entry of the reference vehicle in the assessed tunnel at a speed of 250 km/h or with maximum portal entry speed if it is higher,

g) use the obtained entry pressure wave to calculate the micro-pressure wave emissions,

h) compare the micro-pressure wave emissions with limit values and apply countermeasures if needed.

The last two steps in both of the infrastructure assessment methods are not described in this document. This section only specifies the definition of the interface of the infrastructure corresponding to the vehicle requirement.

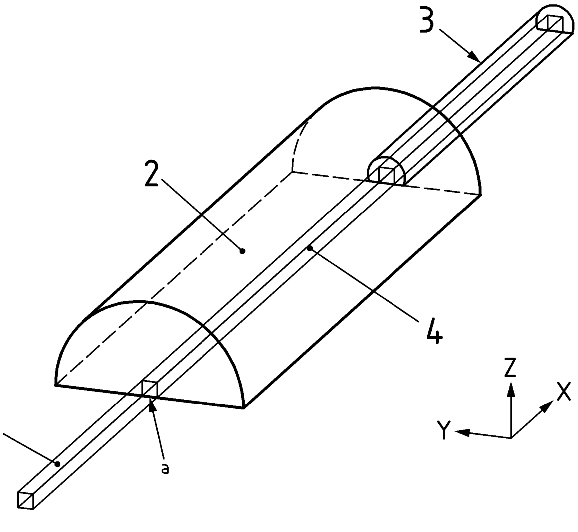
For moving model rig tests, evidence and documentation on the quality and repeatability of the test shall be provided by comparing the maximum entry pressure gradient to those obtained by other laboratories for the reference case or to a full scale test.

7.6.2 Assessment by numerical simulations

All tests shall be performed by three-dimensional simulations using unsteady turbulent compressible models. The simulation tool shall handle moving meshes.

The simulation domain shall consist of a stationary part, containing the tunnel and the open air region in front of the tunnel, and a moving part containing the train. The simulation tool shall handle the region between the stationary and moving parts. The environmental part of the domain outside the tunnel shall be at least as wide as the vertical wall representing the plane of the tunnel portal.

The train nose shall start moving at a distance away from the portal that allows the flow field around the train to establish. At a longitudinal distance of 30 m to 40 m before the portal the flow field shall be stable. Stability of the flow field shall be proven by comparing the nose pressure pulse values at the positions defined in EN 14067-4:2013+A1:2018, 4.1.2 moving along with the train over 10 m to 20 m. An example of a usable simulation domain is shown in Figure 14. Also shown is the coordinate system.



Key

1	“train”
2	stationary domain “environment”
3	stationary domain “tunnel”
4	moving domain “train”
[a]	train nose starts here

Figure 14 — Simulation domain (example)

The train shall be modelled moving into the tunnel portal at a constant speed. An acceleration phase is allowed only at the beginning of the simulation to prevent numerical pressure fluctuations from the simulation propagating through the domain.

In the simulation domain the local mesh spacing may differ. It shall be locally refined in the region near to the train nose, the tunnel portal and the tunnel entry region with a local mesh size of the order 0,1 m. At the far end of the tunnel and in the far field environment, the local mesh size can increase up to 1 m in the x-direction. The time step size shall yield a Courant-Friedrich-Levy (CFL) number, see Formula (17), of the order of 1, based on the local dominant speed U. In the tunnel entry region the train speed is dominant, while in the far tunnel region the pressure wave speed (i.e. the velocity of sound) dominates.

$$\mathrm{CFL} = \frac{\Delta t \cdot \left|U\right|}{\Delta x} \tag{17}$$

The same local meshing rules apply for the moving inner mesh containing the train (both for the reference train and the assessed train). The stationary outer mesh shall be kept identical in both cases.

All walls in the reference simulation as well as in the assessment simulation shall be modelled as smooth walls.

All simulations shall be performed at $\theta = 15\ ^\circ\mathrm{C}$ ambient temperature, at $p_{\mathrm{atm}} = 101\ 325\ \mathrm{Pa}$ ambient pressure and using dry air physical properties. There shall be no applied wind in the open section ahead of the tunnel. There shall be no longitudinal air flow in the tunnel.

All simulations shall be undertaken at full-scale.

The train shall be modelled sufficiently accurately so that modelling simplifications do not result in unrealistic flows. The train nose shape and aerodynamically significant features on the train nose shall be modelled in detail. Permitted simplifications for the train body are:

— no bogies; bogie cavity can be filled for continuous shape;

— no pantographs; cavity can be filled for continuous shape;

— no inter-car gaps.

Friction effects on the train body or at the tunnel wall are of minor importance, because the phenomenon is dominated by compression effects between the train nose and the tunnel portal.

Pressure data are derived from the simulation at a fixed position in the tunnel at a distance of 100 m behind the tunnel portal and at a height of 1,5 m above top of rail. The probe shall be located in the stationary mesh to reduce interpolation errors due to moving mesh nodes. Raw pressure data shall be extracted from all time steps to show that there are no fluctuations/pressure waves before the train nose enters the tunnel.

The pressure gradient is then calculated by a simple linear differential scheme:

$$\left(\frac{\mathrm{dp}}{\mathrm{dt}}\right)_i = \frac{\left(p_{i+1} - p_i\right)}{\left(t_{i+1} - t_i\right)} \tag{18}$$

Additional post-processing, such as data filtering, is permissible by using a Butterworth low pass filter, or equivalent, with a cut-off frequency of between (10 and 15) Hz, but shall be used in the same way for the reference and the assessment simulations. It shall be shown that there is no impact on the comparison if the simulation results are filtered.

7.6.3 Assessment by moving model rig tests

7.6.3.1 Reduced-scale moving model tests (infrastructure)

Reduced scale moving model tests shall be carried out using the assessed tunnel and the reference train according to 7.6.1. The scale of the tunnel and train models shall be such that the Reynolds' number based on the model train speed and a nominal train height of 3 m shall be greater than $2{,}5 \times 10^5$.

It is not required to model the full length of the assessed tunnel; however the model-scale tunnel length shall be at least 300 m at full-scale. The entry portal of the tunnel shall be modelled like the real portal and at the same scale as the tunnel to ensure that the nose entry pressure wave replicates reality. If there is a portal hood, it shall also be modelled at the same scale as the tunnel. The region close to the portal shall be modelled up to a distance of two tunnel diameters above the ground plane, and a minimum of two tunnel diameters each side of the centre line of the tunnel. The ground plane outside the tunnel portal shall extend laterally a minimum of one tunnel diameter from the centre line of the tunnel and a full-scale equivalent of 50 m ahead of the tunnel. The tunnel portal geometry shall be modelled with a tolerance of 50 mm full-scale maximum deviation from the original shape.

The tunnel portal shall be modelled by a vertical wall extending a minimum of two tunnel diameters if the reference tunnel (5.2.2.1) is to be assessed.

The dimensions of the reference train are given in 5.2.2. The train model shall have no additional guiding elements (such as bogies for running on the moving-model rig) for a distance of twice the nose length from the front of the train.

Measurements shall be made inside the tunnel of the pressure transients at a full-scale equivalent of 100 m from the tunnel portal, at a height of the maximum tunnel width on each side of the tunnel. These shall be made with transducers that are able to measure pressures of up to ± 2,5 kPa with a measurement error of less than 1 %. The transducers shall be calibrated prior to use.

The sampling rate shall be at least $5\, v_{\text{tr}}/L_{\text{n,model}}$ Hz. Five separate runs shall be carried out for the assessed train.

NOTE The model scale is given as demonstrated in the following example. For a 1:25 scale model with 5 m nose length full scale and running at 69 m/s, the sampling rate is 1 725 Hz.

The pressure signal p shall be taken as the average between the two sensors on each tunnel side.

The pressure signals shall be transformed to full-scale by

$$p_{\text{fullscale}}\left(\mathrm{t} \cdot R_{\text{model}}\right) = p_{\text{modelscale}}\left(t\right) \tag{19}$$

The pressure gradients may be calculated from Formula (18).

Additional post-processing, such as data filtering is recommended by using a 6th order Butterworth low pass filter, or equivalent, with a cut-off frequency of between 10 Hz × R_{model} and 15 Hz × R_{model}.

For each run, the maximum pressure gradient and the time dependent pressure signal shall be determined at full-scale.

7.6.3.2 Reduced-scale moving model tests (rolling stock)

Reduced scale moving model tests at model speed shall be carried out using the reference tunnel, the reference train and the assessed train according to 7.5.1. The scale of the tunnel and train models shall be such that the Reynolds' number based on the model train speed and a nominal train height of 3 m shall be greater than $2{,}5 \cdot 10^5$. The vehicle surface shall be modelled with a tolerance of 10 mm full-scale maximum deviation from the original shape of the vehicle body.

The model-scale reference tunnel length shall be dimensioned according to 5.2.2. The entry portal of the tunnel shall be modelled by a vertical wall extending a minimum of two tunnel diameters above the ground plane, and a minimum of two tunnel diameters each side of the centre line of the tunnel. The ground plane outside the tunnel portal shall extend laterally a minimum of one tunnel diameter from the centre line of the tunnel and a full-scale equivalent of 50 m away ahead of the tunnel.

The dimensions of the reference train are given in 5.2.2. The length of the assessed train should be the same as the length of the reference train. The assessed train shall be modelled sufficiently accurately that modelling simplifications do not result in unrealistic flows. The train nose shape shall be modelled in detail. Aerodynamically significant features on the train nose shall be modelled in detail. Allowed simplifications for the train body are:

— no bogies, bogie cavity can be filled for continuous shape;

— no pantographs, cavity can be filled for continuous shape;

— no inter car gaps.

The train models (reference and assessed) shall have no additional guiding elements (such as bogies for running on the moving-model rig) for a distance of twice the nose length from the front of the train.

Measurements shall be made inside the tunnel of the pressure transients at a full-scale equivalent of 100 m from the train portal, at the height of the maximum tunnel width on each side of the tunnel. These shall be made with transducers that are able to measure pressures of up to ± 2,5 kPa with a measurement error of less than 1 %. The transducers shall be calibrated prior to use.

The sampling rate shall be at least 5 $v_{\text{tr}}/L_{\text{n,model}}$ Hz. Five separate runs shall be carried out for both the reference train and for the assessed train.

NOTE The model scale is given as demonstrated in the following example. For a 1:25 scale model with 5 m full scale nose length and running at 69 m/s, the sampling rate is 1 725 Hz.

The pressure signal p shall be taken as the average between the two sensors on each tunnel side.

The pressure signals shall be transformed to full-scale by

$$p_{\text{fullscale}}\left(\mathrm{t}\cdot R_{\text{model}}\right)=p_{\text{modelscale}}{}^{\left(t\right)} \tag{20}$$

The pressure gradients may be calculated from Formula (18).

Additional post-processing, such as data filtering is recommended by using a 6th order Butterworth low pass filter, or equivalent, with a cut-off frequency of between 10 × model scale and 15 × model scale Hz.

The conformity with the requirement shall be based on a comparison of the maximum pressure gradient generated by the train nose entry for the reference train and the assessed train.

7.7 Assessment of aerodynamic loads

7.7.1 Assessment of load due to strong wind

Possible methods for determining the static pressure field due to wind include full-scale measurements, CFD simulations or model tests in accordance with EN 14067-4. Regardless of the method for determining the static pressure field the local coefficients for pressure c_{p}, the temperature, air pressure and air density shall be documented and converted to standard conditions, if applicable.

NOTE Presently there are no common assessment procedures or guidelines on the application of the load distribution available.

7.7.2 Assessment of open air passings for fatigue load assessments

External pressure variations act on the investigated train on the side adjacent to a passing train. The values shall be estimated from a table that is set up depending on maximum line speed and the minimum track spacing of the network intended for operation. The table shall comply with the following criteria.

The passing train shall run at maximum line speed and have the most adverse aerodynamic characteristics corresponding to the reference case described in EN 14067-4:2013+A1:2018, 4.1.2, Table 2. For track gauge of 1 435 mm, the stated limit of permissible pressure $\Delta p_{95\,\%,\max}$ is 800 Pa peak-to-peak measured at a distance of $d_x = 2{,}5$ m from the track centre. According to TSI LOC & PAS 2019, the permissible pressure $\Delta p_{95\,\%,\max}$ is constant in the speed range from 160 km/h to 250 km/h. The signal of pressure change is represented in this context by a symmetric pressure change from −400 Pa to 0 Pa and 0 Pa to 400 Pa.

The pressure variations on a wall parallel to track, (here the vertical side of a passing train), shall be assumed to be twice as large as the pressure variations measured in the open air in the absence of such a wall. As track spacings in most networks are depending on the line speed, the effects of track spacing Y_{tr}, vehicle width b and line speed $v_{\text{max,line}}$ and measurement distance d_x (for track gauges other than 1435 mm) should be considered by setting up a table of external pressure change $\pm p_e$, see Table 13 as an example. It is recommended to establish a table for $v_{\text{max,line}}$ using appropriate values for Y_{tr}, b and d_x and the following formulae.

For line speeds below 160 km/h, $\pm p_e$ is provided by Formula (21)

$$\pm p_e = \Delta p_{95\%,\max} \frac{\left(d_x\right)^2}{\left(Y_{\text{tr}} - b/2\right)^2} \cdot \left(\frac{v_{\text{max,line}}}{160}\right)^2 \tag{21}$$

For line speeds 160 km/h to 250 km/h, $\pm p_e$ is provided by Formula (22)

$$\pm p_e = \Delta p_{95\%,\max} \frac{\left(d_x\right)^2}{\left(Y_{\text{tr}} - b/2\right)^2} \tag{22}$$

For line speeds above 250 km/h, $\pm p_e$ is provided by Formula (23)

$$\pm p_e = \Delta p_{95\%,\max} \frac{\left(d_x\right)^2}{\left(Y_{\text{tr}} - b/2\right)^2} \cdot \left(\frac{v_{\text{max,line}}}{250}\right)^2 \tag{23}$$

To cover any operational scenario at lower line speeds, the applied value of pressure changes $\pm p_e$ for open air passing shall always increase with increasing line speed or remain constant at least. In the example in Table 13, the computed value $\pm p_e$ decreases above 200 km/h due to increased track spacing and falls below 800 Pa. Values for 230 km/h to 280 km/h are therefore superseded by the 800 Pa value computed for 200 km/h, see 4th column in Table 13.

Above statements address the nose passing. For each passing train, three pressure variations shall be assumed, representing the passing of the train nose, a coupling of two units and the train tail. Only for crossing trains with a speed below 250 km/h, the pressure variations generated by the coupling (50 % of the nose passing pressure variation) and tail (65 % of the nose passing pressure variation) shall be reduced compared to the one of the nose by the values stated in brackets.

For the purpose of simplification, the assumed internal pressure remains unchanged during passing. Thus, the pressure load, p_L, equals the external pressure change, p_e, on the train.

Table 13 —Example of external pressure change ± p_e computed for maximum line speed and track spacing (taken from [9]):

$v_{\text{line,max}}$ [km/h]	**Track spacing** [m]	**Computed value ± p_e** [Pa]	**Applicable value ± p_e** [Pa]
120	3,8	532	532
130	4,0	528	528
140	4,0	613	613
150	4,0	703	703
160	4,0	800	800
180	4,0	800	800
200	4,0	800	800
230	4,5	556	800
250	4,5	556	800
280	4,5	697	800
300	4,5	800	800
310	4,5	854	854
320	4,5	910	910

7.7.3 Assessment of transient loads in tunnels

7.7.3.1 General

The static pressure load p_L is due to the pressure difference between the external pressure p_e and internal pressure p_i. The pressure p_e is derived from simulated train operations in tunnels and p_i from further calculations taking into account the time series of p_e and the pressure sealing of the vehicle investigated.

$$p_{\text{L}} = p_{\text{i}} - p_{\text{e}} \tag{24}$$

NOTE The pressure difference p_L is defined as $-p_D$, see 7.1.

7.7.3.2 Train parameters

The internal pressure is dependent on the external pressure and it changes with a time delay relative to the external pressure depending on the existing leakage area. One way to determine the time delay of the internal pressure change is the so called tau-model using a time constant τ_{dyn}. The change of the internal pressure can sufficiently be described by the following simplified differential formula:

$$\frac{dp_i}{\text{dt}} = \frac{1}{\tau_{\text{dyn}}}\left[p_e\left(t\right) - p_i\left(t\right)\right] \tag{25}$$

Alternatively, a more detailed internal pressure model may be used.

If the dynamic tau value, τ_{dyn}, representing train operation cannot be approximated from full-scale test results, the following values may be used for a conservative verification depending on an estimate of τ_{dyn} (see the values in brackets). Larger τ_{dyn} values will result in larger aerodynamic loads:

— non-pressure tight vehicle (τ_{dyn} < 0,5 s) calculate with τ_{dyn} = 0,5 s;

— moderately pressure tight vehicle (0,5 s ≤ τ_{dyn} < 4 s) calculate with τ_{dyn} = 8 s;

— pressure tight vehicle (τ_{dyn} ≥ 4 s) calculate with τ_{dyn} = 50 s.

A non-pressure tight vehicle is characterized by an absence of pressure protection measures, such as pressure protection flaps, pressure protection fans and pressure tight gangways between the cars. It may be necessary to use different tau values for pressure tight and non-pressure tight areas, (e.g. different values for the driver's cab and engine room of a locomotive).

For both the train of interest and the encountering train, the respective maximum operating speed or, when lower, the maximum line speed in that section shall be considered. The aerodynamic characteristic of the crossing train has two possible states, and depends on the speed in the tunnel under investigation. The characteristics shall be selected to meet or to be greater than the three pressures stated for Δp_{N}, Δp_{N}+ Δp_{Fr} *and* Δp_{N}+ Δp_{Fr}+ Δp_{T} in Table 2 in 5.1.2.2. The characteristics of the investigated train may be estimated based on comparison with measurements of similar full-scale trains.

The length of the encountering train is always 400 m. For assessed trains in fixed formation or operation with multiple units, it is sufficient to investigate the maximum length only. Vehicles for general operation shall be investigated assuming a train with 200 m length if their maximum speeds are equal to or below 200 km/h; for other speeds a train length of 400 m shall be assumed. The properties of unknown vehicles shall be chosen to approximate as closely as possible the characteristic of Table 2 in 5.1.2.2. A constant cross-section and perimeter can be assumed for the purpose of simplification over the whole length. If the cross-sectional area of the vehicle varies, the area of the first car shall be used.

7.7.3.3 Tunnel parameters

Tunnels may be simplified in the simulation model. It is sufficient to model them as simplified non-inclined tubes with no air ducts and constant cross-section. The cross-sectional area and length, as well as the friction coefficient used shall be documented. Tunnel friction is required; A value of 0,005 for $C_{\text{f,tu}}$ is suggested, representing a tunnel with smooth walls e.g. modern concrete lined with ballast and track.

7.7.3.4 Simulation parameters

The resulting signal of pressure varying over time shall have a calculation resolution of no more than 0,1 s.

If the crossing of two trains is assessed, the train to be examined enters the tunnel by definition at the time t = 0 s. When two trains meet, the difference in entry time is given by t_{e}. A positive value of t_{e} refers to a situation where train 1 enters before train 2 (crossing train). To identify correctly the worst crossing conditions, simulations shall be performed over an interval time between:

$$-\frac{114+99\cdot\ln\left(\dfrac{v_{\text{tr},2}}{v_{\text{tr},1}}\right)}{\dfrac{L_{\text{tu}}}{1000}+1}\cdot\frac{L_{\text{tu}}}{c}-\frac{L_{\text{tu}}+L_{\text{tr},2}}{v_{\text{tr},2}}\le t_{\text{e}}\le\frac{L_{\text{tu}}+L_{\text{tr},1}}{v_{\text{tr},1}} \tag{26}$$

NOTE The formula covers train crossings and aerodynamic crossings in tunnels with remaining pressure waves down to 10 % of their initial amplitude. A refined formula can be found in [9].

The time increment Δt_e within the interval above is given by Formula (27), but shall be limited to a maximum of 0,5 s.

$$\Delta t_e = \frac{L_{\mathrm{tr},1}}{2\left(v_{\mathrm{tr},1} + v_{\mathrm{tr},2}\right)} \tag{27}$$

The external pressure signal is determined for at least three measuring positions on the simulated train. These positions are defined as follows:

x_1 = at the start of the constant cross-section but at least 5 m from the nose of the train, as maximum positive pressures are expected here,

x_2 = in the centre of the train,

x_3 = at the end of the constant cross-section but at least 5 m in front of the end of the train, as severe negative pressures are expected here.

If the position of a single specified vehicle of interest in the trainset is known, the measuring position can be limited to the centre of this vehicle. The effect of the direction of travel shall be taken into account.

7.7.3.5 Calculation software

The calculation of the pressure waves for determining the loads in the tunnel based on a one-dimensional propagation is sufficient. Validated software shall be used. The software including its release date/version and a short description of the calculation procedures shall be documented.

7.7.3.6 Assessment

For the reference cases defined in 5.3.2.6, the maximum pressure difference p_d shall be determined from simulations of single train tunnel passings and train crossings investigating the full interval of entry times, see7.7.3.4.

If the scenario in 5.3.2.5 does not include a tunnel length definition, the tunnel length shall be selected which is expected to produce the maximum exterior pressure change. The critical tunnel length $L_{\mathrm{tu,crit}}$ which leads to the largest negative pressure outside of the train in the single train situation is approximately:

$$L_{\mathrm{tu,crit}} \approx \frac{L_{\mathrm{tr}}}{4} \frac{c}{v_{\mathrm{tr}}} \left(1 + \frac{c}{v_{\mathrm{tr}}}\right) \tag{28}$$

The critical tunnel length $L_{\mathrm{tu,crit}}$ which leads to the maximum negative pressure outside of the train in the two train crossing situation is approximately:

$$L_{\mathrm{tu,crit}} \approx \frac{c}{2} \left(\frac{L_{\mathrm{tr},1}}{v_{\mathrm{tr},1}} + \frac{L_{\mathrm{tr},2}}{v_{\mathrm{tr},2}}\right) \tag{29}$$

For unsealed trains, larger loads may occur in other tunnel lengths. In this case, a variation of investigated tunnel lengths may be applied, or alternative approaches may be used (see guideline [9] 5.2.2.1 as an example for such an assessment).

The maximum value of the pressure differences, p_d, from all tunnel operation reference cases shall be considered for a proof of structural strength of the vehicle body.

The loads determined using the above method are sufficiently conservative to EN 12663-1 and do not require any additional safety factor.

7.7.3.7 Documentation

The parameters used for the investigated and encountering trains, including the friction and loss coefficients, shall be documented and justified. The pressure signal of the encountering train shall be compared in a diagram to the reference case defined in 5.1.2.2 and the values in Table 2. Evidence of the simulation tool validation with full-scale measurements shall be provided, e.g. as indicated in informative Annex E.

7.7.4 Assessment of fatigue loads

7.7.4.1 General

A train travelling for its full lifetime on the route defined in the reference case shall sustain the aerodynamic loads acting on the vehicle body for any operation covered by the reference case. Such loads are applicable to be used in structural strength assessments of vehicle bodies only.

For each route section, consisting of open air sections, single train tunnel transits and crossings in tunnels, an individual load collective *C* can be determined. These three load collective types shall be combined and result in:

- a load collective for trains passing in the open air based on 7.7.2;
- a load collective for tunnels (single train transits and trains crossing in tunnels, see below).

It may be assumed, that the above load collectives can be combined into a single load collective, to describe the amplitudes of pressures acting on all sides of the train. The load collective shall be scaled to represent the lifetime of the train. This load collective *C* is the output of the assessment. It shall be applied equally distributed over the surfaces of the structures creating the pressure tightness of the vehicle. The loads on openings in the vehicle body, like windows and doors, shall be accounted for. It shall additionally be converted into a load collective diagram with sum frequencies and an equivalent load for a specific number of load cycles.

The approach for fatigue is similar to that for exceptional loads in 7.7.3. Therefore, all the requirements stated for the train, tunnel, simulation parameters and calculation software in 7.7.3.2 to 7.7.3.5 shall be applied.

7.7.4.2 Load collectives

Load collectives *C* result from rainflow classification of the time signals of pressure load p_L scaled for the specified service life of the vehicle. For the load collective of a trains crossing in tunnels, a collation of time signals covering the variation of entry time t_e shall be analysed.

Define a reference route from A to B consisting of N_oa sections of open track and N_tu tunnels, in which solo passages or train crossings occur.

The load collective for trains meeting on the open track $C_\mathrm{oa,cros}$ is derived from the values of train meetings on the open track in the individual sections, where the number of passages over the service life on this section of the route is taken into account:

$$C_\mathrm{oa,cros} = \sum_i \left(C_{\mathrm{oa,cros},i} \cdot n_{\mathrm{oa,cros},i} \right) \cdot t_\mathrm{life} \cdot \frac{L_{\mathrm{year},i}}{L_{\mathrm{section},i}} \tag{30}$$

where

$i = 1, \ldots, N_\mathrm{oa.}$

It is assumed, that the pressure due to “passing other trains in open air” and due to “tunnel events” may be treated in one collective and the resulting simplified application of an equivalent load. The frequency for trains crossing on the open track accounts for this by use of a factor of 0,5, see Formula (37).

The collective for solo passages in the tunnel is calculated in a similar way:

$$C_{\mathrm{tu,solo}} = \sum_{j} \left(C_{\mathrm{tu,solo,j}} \cdot n_{\mathrm{tu,solo,j}} \right) \cdot t_{\mathrm{life}} \cdot \frac{L_{\mathrm{year},j}}{L_{\mathrm{section},j}} \qquad (31)$$

where

$$j = 1, \ldots, N_{\mathrm{tu}} \qquad (32)$$

The load collective for two trains encountering in a tunnel is derived from multiple simulation runs for different entry times t_e. The number of calculated entry time gaps $N_{\Delta te,j}$ shall also be taken into account in order to standardize the collective to represent a single tunnel passage with a crossing.

$$C_{\mathrm{tu,cros}} = \sum_{j} \left(C_{\mathrm{tu,cros},j} \cdot n_{\mathrm{tu,cros},j} \cdot \frac{1}{N_{\Delta te,j}} \right) \cdot t_{\mathrm{life}} \cdot \frac{L_{\mathrm{year},j}}{L_{\mathrm{section},j}} \qquad (33)$$

The load collective for the operational lifetime $C_{\mathrm{lifecycle}}$ is the output parameter to be used in structural strength fatigue analysis. It results from the sum of the above individual collectives:

$$C_{\mathrm{lifecycle}} = C_{\mathrm{oa,cros}} + C_{\mathrm{tu,solo}} + C_{\mathrm{tu,cros}} \qquad (34)$$

With this process, several reference route segments including train encountering can be combined into one load collective. For each measuring position defined in 7.7.3.4, one load collective is determined. Based on the assumption that both directions are equally frequented and the train configuration is symmetric, the loads at the measuring position x_1 and x_3 may be combined as follows:

$$C_{\mathrm{lifecycle}} = \frac{1}{2} \cdot C_{\mathrm{lifecycle,front}} + \frac{1}{2} \cdot C_{\mathrm{lifecycle,tail}} \qquad (35)$$

7.7.4.3 Train crossing frequencies

How often trains cross depends on the length of the route section $L_{\mathrm{section},i}$, the train speed $v_{\mathrm{tr},1}$, the speed of the encountering train $v_{\mathrm{tr},2}$ and the number of trains per hour in opposite direction at a stationary point $N_{\mathrm{trainsperhour}}$.

For crossing on open track, the load exerted on the vehicle body is generally acting only on the side adjacent to the encountering train. If an equal distribution of train encounters on both sides can be expected, the number of train encounters can be halved to obtain one load cycle acting on the whole vehicle body. The frequency for trains crossing on the open track is in this case determined as follows:

$$n_{\mathrm{oa,cros},i} = \frac{1}{2} \cdot L_{\mathrm{section},i} \cdot N_{\mathrm{trainsperhour}} \cdot \frac{v_{\mathrm{tr,1}} + v_{\mathrm{tr,2}}}{v_{\mathrm{tr,1}} \cdot v_{\mathrm{tr,2}}} \qquad (36)$$

where

i is defined above.

The number of train encounters in a tunnel is calculated based on the virtual length of the tunnel L_{virttun}. The virtual length originates from the fact that residual pressure waves may still propagate in the tunnel after the opposing train has already left the tunnel. The virtual length of the tunnel is calculated by

$$L_{\mathrm{virttun},j} = \left(t_{\mathrm{e,max}} - t_{\mathrm{e,min}}\right) \cdot \frac{v_{\mathrm{tr},1} \cdot v_{\mathrm{tr},2}}{v_{\mathrm{tr},1} + v_{\mathrm{tr},2}} \tag{37}$$

The frequency for trains crossing in a double track tunnel is determined by:

$$n_{\mathrm{tu,cros},j} = L_{\mathrm{virttun},j} \cdot N_{\mathrm{trainsperhour}} \cdot \frac{v_{\mathrm{tr},1} + v_{\mathrm{tr},2}}{v_{\mathrm{tr},1} \cdot v_{\mathrm{tr},2}} = \left(t_{\mathrm{e,max}} - t_{\mathrm{e,min}}\right) \cdot N_{\mathrm{trainsperhour}} \tag{38}$$

but is limited to $0 \le n_{\mathrm{tu,cros},j} \le 1$.

The frequency of single train passages without train encounters in a double track tunnel is determined by:

$$n_{\mathrm{tu,solo},j} = 1 - n_{\mathrm{tu,cros},j} \tag{39}$$

7.7.4.4 Rainflow analysis

The time signals of p_{L} shall be evaluated by means of the rainflow procedure (see [22]), unless required differently by structural strength methods. As load collectives of the individual track sections have to be combined to determine the overall load collective, only rainflow-counting algorithms are suitable that take into account the residual (see EN 17149:—[1], 7.3.3). The rainflow collectives of the partial collectives are added up directly. The residuals are strung together in the corresponding order and analysed again. The rainflow collective of the residuals is then added to the sum of collectives. The remaining residual is counted by closing it cyclically and adding it to the overall collective. A suitable algorithm is, e.g. the so-called 4-point algorithm. This method divides all local extreme values of the pressure time series into start and goal categories or into categories based on their amplitude and their average value. The so-called rainflow matrix contains the frequencies of the corresponding classified values.

The class range is 100 Pa. If the number of classes used is less than 32 a class range of 50 Pa shall be selected.

7.7.5 Determination of the damage-equivalent load amplitude for scenario

In order to have a single load value to compare different running scenarios, the rainflow matrix shall be transferred to the damage-equivalent amplitude assuming uniform material values.

NOTE This value is not generally valid for a strength analysis.

The damage-equivalent amplitude p_{eq} is determined below. Based on the amplitudes, p_{l}, and the corresponding frequencies, h_{l}, the damage-equivalent amplitude, p_{eq}, should be calculated for the reference cycles $N_{\mathrm{c}} = 10^7$ and the S-N curve exponent $k = 3$ by:

AC⟩

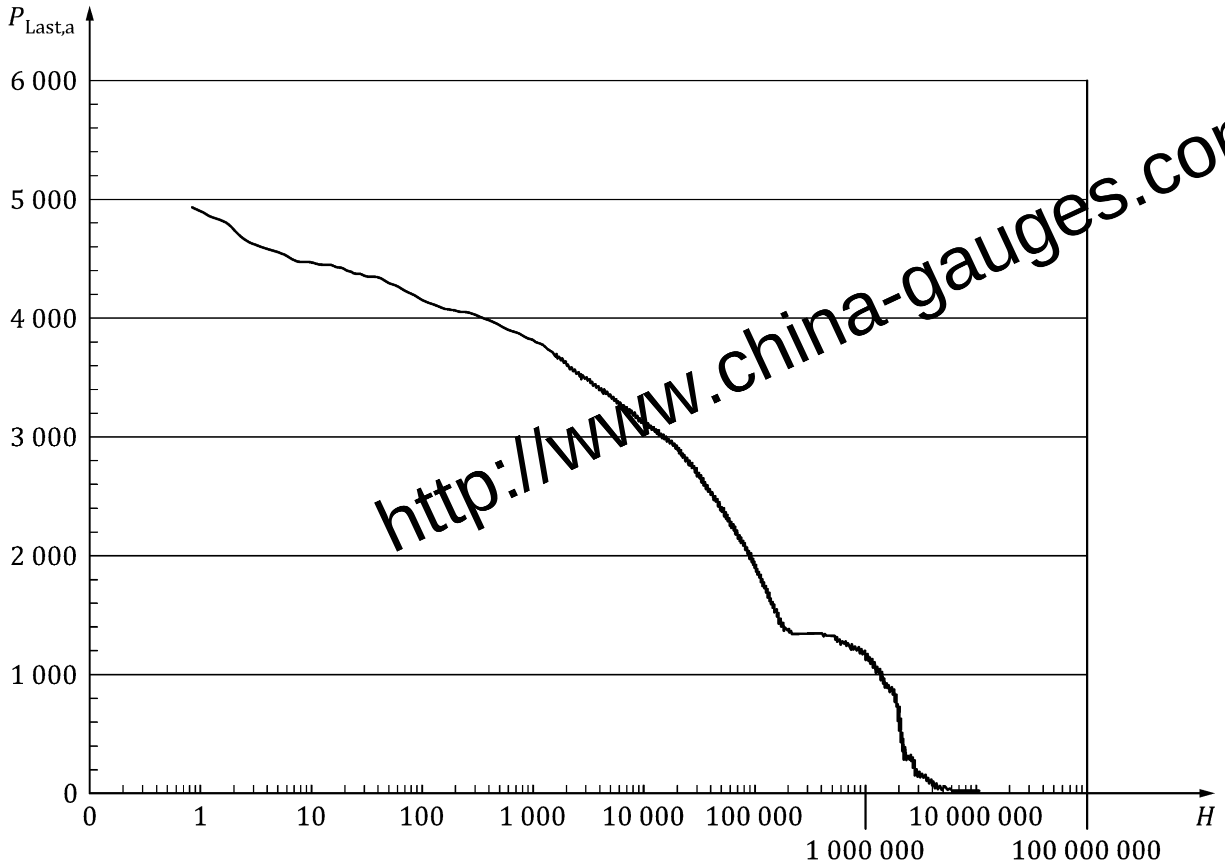
$$p_{\mathrm{eq}} = \left(\frac{\sum_{l} h_{\mathrm{l}} \cdot p_{\mathrm{l}}^{\mathrm{k}}}{N_{\mathrm{c}}}\right)^{\frac{1}{k}} \tag{40}$$

⟨AC

7.7.6 Documentation

The following items shall be documented to determine the fatigue loads:

- Route data including the type and frequency of oncoming traffic:
    - service life and travelling distance of the vehicle under consideration;
    - the parameters used for the investigated and encountering trains including the friction and loss coefficients, shall be documented and justified. The pressure signal of the encountering train shall be compared in a diagram to the reference case defined in 5.1.2.2 and the values in Table 2. Evidence on the simulation tool validation to full-scale measurements and to the calculation procedure of the damage-equivalent amplitude shall be provided, e.g. see informative Annex E;
    - samples of both exterior pressure signals and differential pressure signals, for at least one representative single train tunnel passage and one passage where two trains pass in the tunnel;
    - exterior pressure signals and differential pressure signals for scenarios each with maximum positive loads and maximum negative loads;
    - a rainflow matrix diagram for the measuring position at the centre of the vehicle scaled to lifetime operation;
    - pressure load collective diagram for the head, centre and rear of the train in the form of the sum frequency over the amplitude. Here, the amplitude values shall be applied to the linearly divided y-axis and the sum frequency to the logarithmically divided x-axis. The frequencies shall be extended to the projected service life of the vehicle (scaling). Figure 15 provides an example;
- the damage-equivalent amplitudes for comparison as defined above.



Key

1 pressure difference amplitude p_l in Pascal

2 sum frequency H (log)

Figure 15 — Example of a load collective diagram with sum frequencies

7.7.7 Simplified load cases

7.7.7.1 General

For non-pressure tight vehicles (see 7.7.3.2) that are not deemed to operate on lines with maximum line speeds above 200 km/h, the load cases in Table 14 may be applied to a complete rail vehicle body. Loads on smaller components may be significantly larger.

NOTE Lines with two tracks are assumed, so trains can cross at maximum line speed.

7.7.7.2 Exceptional loads

The exceptional load according to Table 14 covers loads due to strong wind, tunnel operation and trains crossing. The loads shall be applied perpendicular to and from all directions relative to the surface of the vehicle.

Table 14 — Simplified exceptional load cases for unsealed vehicles

Maximum design speed km/h	**Load** Pa
$v_{\text{tr,max}} \leq 160$	± 1 900
$160 < v_{\text{tr,max}} \leq 200$	± 2 500

NOTE Values in Table 14 correspond to UIC 566 and were validated for track and tunnel parameters of the conventional German network.

7.7.7.3 Fatigue loads

The fatigue loads according to Table 15 cover loads due to tunnel operation and trains crossing in the open air. The loads shall be applied perpendicular to and from all directions onto the surface of the vehicle.

Table 15 — Simplified fatigue loads for 10^7 changes of load for unsealed vehicles

Maximum design speed km/h	**Load** Pa
$v_{\text{tr,max}} \leq 200$	± 800

NOTE Values in Table 15 were validated for the track and tunnel parameters of the conventional German network.

7.8 Assessment of pressure sealing

7.8.1 General

There are three requirements for undertaking pressure sealing assessments of rail vehicles. The first is associated with the assessment of aural pressure comfort for passengers and staff in trains. The second is for the assessment of pressure loading on the rail vehicle structures during transits primarily through tunnels, but also when passing other trains in the open air. The final requirement is for detecting leakage paths through the train structure as part of the process to improve the sealing of the vehicles.

External pressures generated by a train passing through a tunnel are modified inside the train by the degree of pressure sealing and this is used to control aural comfort, (see Annex B for details of pressure comfort criteria). In turn, this leads to pressure loads across the train structure as the internal and external pressures will not be the same, (see Annex D for details of pressure loadings in tunnels on unsealed trains).

Pressure fluctuations outside a pressure sealed train vehicle can change the pressures inside the vehicle by two main mechanisms:

a) The vehicle is deformed by the external pressure with a consequent change of volume. It has been estimated that the internal pressure may vary by up to 10 % of the external pressure change through this mechanism.

b) The pressure difference between the interior and exterior of the vehicle forces air through any leakage paths, so that the internal pressure follows the external pressure changes with a time delay and attenuation.

Due to these two mechanisms, a way is needed to describe how the internal pressure responds to the external pressure changes. This is normally achieved by defining the air tightness of a train vehicle in terms of either a pressure tightness coefficient, τ, or an equivalent leakage area, S_{eq}. It is also a common assumption that the vehicle volume is considered as constant, despite its being dynamically deformable, and that the effects due to (a) above can be ignored. The air-tightness of a vehicle differs when it is stationary compared to when it is moving. In the latter case, small movements of the structure of the vehicle relative to each other may alter the leakage paths, or leakage paths, which are relatively sealed when it is static, may open up due to the movement of the vehicle. There are thus dynamic, τ_{dyn}, and static, τ_{stat}, values of pressure tightness coefficient for rail vehicles. The values of τ_{stat}, τ_{dyn} and S_{eq} depend on the value of the pressure difference and, in particular, on the sign of the pressure difference.

Due to its ease of measurement, static values of air-tightness are often used in the vehicle production to approximate the dynamic air-tightness of a vehicle in operation, even though the latter may be several times smaller than the former.

7.8.2 Dynamic pressure tightness

The air-tightness of a rail vehicle subject to a dynamically varying external pressure, τ_{dyn}, is defined via the formula:

$$\frac{dp_i\left(t\right)}{\mathrm{dt}} = \frac{k_r}{1+k_r}\cdot\frac{dp_e\left(t\right)}{\mathrm{dt}} + \frac{1}{\tau_{\mathrm{dyn}}\left(1+k_r\right)}\Delta p\left(t\right) = \frac{k_r}{1+k_r}\cdot\frac{dp_e\left(t\right)}{\mathrm{dt}} + \frac{1}{\tau_{\mathrm{dyn}}\left(1+k_r\right)}\left(p_e\left(t\right)-p_i\left(t\right)\right) \qquad (41)$$

where:

$\Delta p(t)$ is the differential pressure, $(p_e - p_i)$, at time t, (Pa);

p_e is the pressure external to the train, which varies with time (= $p_e(t)$), (Pa);

p_i is the train internal pressure, which varies with time (= $p_i(t)$), (Pa);

k_r is the vehicle structural rigidity factor (-).

The factor, k_r, is a measure of the rigidity of the structure and represents the degree of external pressure loading that transmits to the interior of the vehicle. If k_r is not taken into account, the air tightness of the vehicle will be overestimated. Values of k_r lie in the range 0,05 to 0,1 for modern high speed passenger vehicles. Ref [15] gives a method for determining k_r for a vehicle subjected to an instantaneous external pressure change. If k_r is not known, it may be assumed to take the value $k_r = 0{,}1$.

For a structurally rigid vehicle or if k_r is ignored, $k_r = 0$, and Formula (41) becomes:

$$\frac{dp_i\left(t\right)}{\mathrm{dt}} = \frac{1}{\tau_{\mathrm{dyn}}}\Delta p\left(t\right) = \frac{1}{\tau_{\mathrm{dyn}}}\left(p_e\left(t\right)-p_i\left(t\right)\right) \qquad (42)$$

7.8.3 Equivalent leakage area

The rate of change of the internal pressure, p_i, can also be expressed in terms of the equivalent leakage area, S_{eq}, as:

$$\frac{dp_i}{\mathrm{dt}} = \frac{k_r}{1+k_r}\cdot\frac{dp_e\left(t\right)}{\mathrm{dt}} + \mathrm{sgn}\left(\Delta p\left(t\right)\right)\cdot\frac{c^2 S_{\mathrm{eq}}}{V_{\mathrm{int}}\left(1+k_r\right)}\sqrt{2\rho_{\mathrm{amb}}\left|\Delta p\left(t\right)\right|} \qquad (43)$$

where

c is the speed of sound, (m/s);

V_{int} is the internal volume of the vehicle, (m^3);

ρ_{amb} is the ambient atmospheric air density, (kg/m^3);

S_{eq} is the equivalent leakage area, (m^2).

For a structurally rigid vehicle or if k_r is ignored, Formula (43) becomes:

$$\frac{dp_i}{\mathrm{dt}} = \mathrm{sgn}\left(\Delta p\left(t\right)\right)\cdot\frac{c^2 S_{\mathrm{eq}}}{V_{\mathrm{int}}}\sqrt{2\rho_{\mathrm{amb}}\left|\Delta p\left(t\right)\right|} \qquad (44)$$

7.8.4 Test methods

7.8.4.1 General

There are two main test approaches to measuring the air-tightness of train vehicles. In each case, pressures are measured inside and outside the train. The pressure tightness is determined by considering how the relative pressure changes with time, as the internal pressure tries to equalize to the external pressure via leakage. Further information on air tightness may be found in Ref [16].

The first test approach is a static pressurization test of a single train vehicle. The second method involves testing a vehicle or set of vehicles in a train as it is in movement. In both types of test pressures are measured inside and outside the train. The pressure tightness values obtained in each case are different for the reasons mentioned above.

7.8.4.2 Static tests

In a static test, the pressure outside the train vehicle is constant. Tests shall be undertaken on a complete single train vehicle with its ends sealed at the gangway connection. Any air leakage by the end seals shall be negligible and shall be confirmed by a suitable test.

NOTE 1 Ref [17] gives a method for testing the air tightness of sub-assemblies and components.

The vehicle should be placed in the test location sufficiently far in advance that the air conditions, (pressure, temperature, humidity), inside become stabilized with respect to the exterior conditions.

Any systems installed that normally control pressure changes in tunnels, such as active shutter covers, shall be set into their normal tunnel operational states or alternative measures put in place.

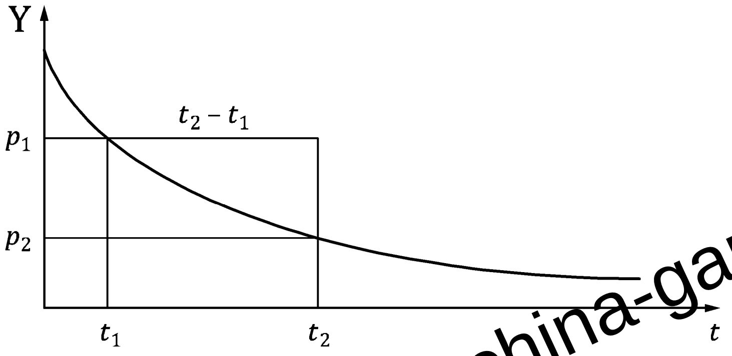
Pressures shall be measured using transducers on the exterior and interior of the vehicle. These shall be calibrated prior to use over the expected pressure range, typically up to ± 4 kPa. The measurement error should be less than 2 %. The internal transducer location should be away from the air supply and away from any suspected air leakage paths. In general, a suitable location is at the middle of the vehicle.

The absolute pressure of the air outside the vehicle, p_{atm}, shall be measured throughout the tests. Temperature shall be measured and humidity should be monitored inside and outside the vehicle during the test. Acquisition of pressure, temperature and humidity shall comply with ISO 8756.

A suitable device, (e.g. a fan, compressed air), shall then either blow air into or extract air from the sealed vehicle. The resulting pressure difference between inside and outside shall be representative of the expected operation in tunnels. A typical value is up to 4 kPa. The device providing the pressurization shall be sealed at the point of entry to the vehicle, and shall be capable of being shut off rapidly without any air leakage to allow an accurate definition of the internal pressure at the start of the test. Nevertheless, there should be a delay to allow stabilization of any residual variations of the internal pressure before starting to record the internal pressure time history.

NOTE 2 Values of air tightness when measured using an over-pressure method can differ from values measured during an under-pressure method, as individual leakage paths can change, open or close according to the pressure differential.

The internal pressure relative to ambient is designated as p_1. Once the required level of pressure difference has been attained at time t_1, the fan shall be switched off and the time shall be measured until the relative pressure reaches a value p_2 at time t_2. Figure 16 is a schematic showing the pressure variation with time.



Key

p_1 and p_2 internal pressure
t, t_1 and t_2 time
Y pressure

Figure 16 — Schematic of the pressure decay in a static pressure test

Tests may proceed when the temperature difference between the inside and outside of the vehicle is less than 5 K.

If equivalent leakage area is being determined, the internal volume, V_{int}, of the vehicle shall also be determined. The measurement error shall be less than 5 %.

For a constant external pressure, Formula (41) can be solved to obtain the following expression for τ_{stat},

$$\tau_{\text{stat}} = \frac{t_2 - t_1}{\left(1 + k_{\text{r}}\right)\ln\left(p_1 / p_2\right)} \tag{45}$$

If p_2 is chosen such that the ratio of p_1 to p_2 is equal to $e = 2{,}718$, then $\tau_{\text{stat}} = (t_2 - t_1)$. Table 16 below gives some example pairs of p_1 and p_2 which satisfy this relationship.

Table 16 — Example values of p_1 and p_2 pairs

p_1 Pa	p_2 Pa
4 000	1 470
3 500	1 290
3 000	1 100

For a constant external pressure, Formula (43) can be solved to give the following expression:

$$p_2 = \operatorname{sgn}\left(p_1\right)\cdot\left(-\frac{c^2 S_{\text{eq}}\left(t_2 - t_1\right)}{V_{\text{int}}\left(1 + k_{\text{r}}\right)}\sqrt{\frac{\rho_{\text{amb}}}{2}} + \sqrt{p_1}\right)^2 \quad \text{for} \quad t_2 \in \left[t_1, \frac{V_{\text{int}}}{c^2 S_{\text{eq}}}\cdot\sqrt{\frac{2p_1}{\rho_{\text{amb}}}}\right] \tag{46}$$

This solution can also give an expression for S_{eq}:

$$S_{\text{eq}} = \frac{V_{\text{int}}\left(1 + k_{\text{r}}\right)}{c^2\left(t_2 - t_1\right)}\cdot\sqrt{\left(\frac{2}{\rho_{\text{amb}}}\right)}\cdot\left(\sqrt{p_1} - \sqrt{p_2}\right) \tag{47}$$

The ambient air density ρ_{amb}, shall be calculated for the test conditions using the measured external pressure, temperature, using the Formula (12). It is not necessary to allow for the effect of humidity in the determination of density for this type of test, therefore it may be set to zero.

The speed of sound, c, shall be calculated from:

$$c = \sqrt{\gamma \frac{p_{\mathrm{atm}}}{\rho_{\mathrm{amb}}}} \tag{48}$$

where γ is the adiabatic index of air.

NOTE 3 It is good practice to repeat tests and the average leakage values obtained.

An alternative test consists in a set up where a constant volume flow into or out of the vehicle is generated and the pressure difference is measured. The appropriate formula can be found in EN 14752:2019, Annex C.

7.8.5 Dynamic tests

In a dynamic test, the value(s) of τ_{dyn} is determined by comparing the temporal variations of the train's external and internal pressures during passage through a tunnel.

Pressures are measured using transducers on the exterior and interior of the train. These shall be calibrated prior to use over the expected pressure range, typically ± 4 kPa. The measurement error shall be less than 2 %.

As a minimum, external pressure shall be measured at the nose of the train, in the middle and just ahead of the tail.

If there is significant internal sealing between vehicles, it is also recommended to perform internal and external pressure measurements on other cars, in addition to the first, the last and the middle car.

It may be sufficient to make a measurement of a single internal pressure, if the vehicles of the train are not separately sealed, (e.g. with internal sealing doors) and the internal pressure is representative of the pressure field inside the whole train. The internal measurements should be made close to the measurement positions of the external measurements.

Shutters that are used to control pressures inside the train during transit through tunnels shall be closed during the assessed testing period.

The speed of the train shall be known with a precision of 1 % and it is recommended that it should be constant during the passage through the tunnel, to avoid air inertial effects within the train.

Data shall be sampled at a rate of 5 $v_{\mathrm{tr}}/L_{\mathrm{n}}$ Hz or greater, with anti-aliasing filters having a cut-off frequency of at most one quarter of the sampling rate. The results from the test will consist of time histories of pressures external and internal to the train at a number of locations along the train. The pressure tightness coefficient is determined by comparing the internal pressures with the external pressures at the same positions along the train.

These may be analysed as follows to determine the value (s) of τ_{dyn}.

Formula (41) can be written in finite difference form from Ref. [18] as:

$$\frac{p_i\left(t+\Delta t\right)-p_i\left(t\right)}{\Delta t}+\frac{1}{2\tau_{\mathrm{dyn}}\left(1+k_{\mathrm{r}}\right)}\cdot\left(p_i\left(t+\Delta t\right)+p_i\left(t\right)\right)=$$

$$\frac{1}{2\tau_{\mathrm{dyn}}\left(1+k_{\mathrm{r}}\right)}\cdot\left(p_e\left(t+\Delta t\right)+p_e\left(t\right)\right)+\frac{k_{\mathrm{r}}}{\left(1+k_{\mathrm{r}}\right)}\cdot\left(\frac{p_e\left(t+\Delta t\right)-p_e\left(t\right)}{\Delta t}\right) \tag{49}$$

which relates internal pressures to external pressures at times t and $t + \Delta t$. Successive values of τ_{dyn} shall be chosen so that calculated values of the internal pressure match the measured values for each time step.

NOTE It could be necessary to choose different values of τ_{dyn} according to the sign (positive/negative) of the pressure difference between the outside and the inside of the train.

It is permissible to use other methods of analysis to obtain τ_{dyn} values. Consideration of the internal harmonization of pressures may be necessary to include in such an analysis.

To obtain single values of τ_{dyn}, an optimization of the comparison will be necessary using a best fit statistical approach or equivalent.

In general, external and internal pressures at equivalent locations along the train shall be analysed to obtain τ_{dyn}. It is expected that the values obtained will be different due to variations in leakage along the train and air inertial effects within the train.

When limited internal pressure measurements are made, the comparison should be made with the external pressure obtained by averaging the external pressures at the external measurement points closest to the internal pressure measurement location.

Annex A
(informative)

Predictive formulae

A.1 General

The following predictive formulae allow estimation of the different pressure changes of the train-tunnel-pressure signature and the aerodynamic drag.

A.2 SNCF approach[3]

A.2.1 Entry of the nose of the train

The amplitude of the wave front can be determined using the following formula:

$$\Delta p_N = \kappa p_0 \mathrm{Ma}\left[1 - \frac{\sqrt{1+2Y} - 1}{Y}\right] \tag{A.1}$$

where

$$Y = \zeta_n \mathrm{Ma}\left(\frac{1}{\left(1-B\right)^2} - 1\right) \tag{A.2}$$

and

$$\zeta_n = 1 + \frac{\zeta_\mathrm{h}}{1-\left(1-B\right)^2} \tag{A.3}$$

A.2.2 Entry of the body of the train

The formula for quantifying Δp_fr is as follows:

$$\Delta p_\mathrm{fr} = \kappa p_0 \mathrm{Ma} X_4\left[1 + \frac{2L_\mathrm{tr}}{D_\mathrm{h,tu}} C_\mathrm{f,tu}\left(1-\mathrm{Ma}\right) X_4\right] - \Delta p_N \tag{A.4}$$

where

$$X_1 = \frac{4L_\mathrm{tr}}{D_\mathrm{h,tu}}\left[C_\mathrm{f,tu}\left(\frac{1}{\mathrm{Ma}} - 1\right) - \frac{1}{\left(1-B\right)^3}\left(C_\mathrm{f,tr}\sqrt{B} + C_\mathrm{f,tu}\right)\right] - \zeta_n\left(\frac{1}{\left(1-B\right)^2} - 1\right) \tag{A.5}$$

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[3] Gregoire et al. [1]

$$X_2 = \frac{1}{\mathrm{Ma}} + \frac{4L_{\mathrm{tr}}}{D_{\mathrm{h,tu}}} C_{\mathrm{f,tu}} \left[\frac{1}{\mathrm{Ma}} - 1 - \frac{1}{\left(1-B\right)^2} \right] \qquad \text{(A.6)}$$

$$X_3 = \frac{2}{\mathrm{Ma}} + \frac{4L_{\mathrm{tr}}}{D_{\mathrm{h,tu}}} C_{\mathrm{f,tu}} \left[\frac{1}{\mathrm{Ma}} - 1 - \frac{1}{\left(1-B\right)} \right] \qquad \text{(A.7)}$$

$$X_4 = 1 + \frac{-X_2 + \sqrt{X_2^2 - X_1 X_3}}{X_1} \qquad \text{(A.8)}$$

A.2.3 Entry of the rear of the train

Δp_{T} can be approximated as $\Delta p_{\mathrm{T}} = 0{,}8\ \Delta p_{\mathrm{N}}$

A.3 TU Vienna approach[4]

A.3.1 General

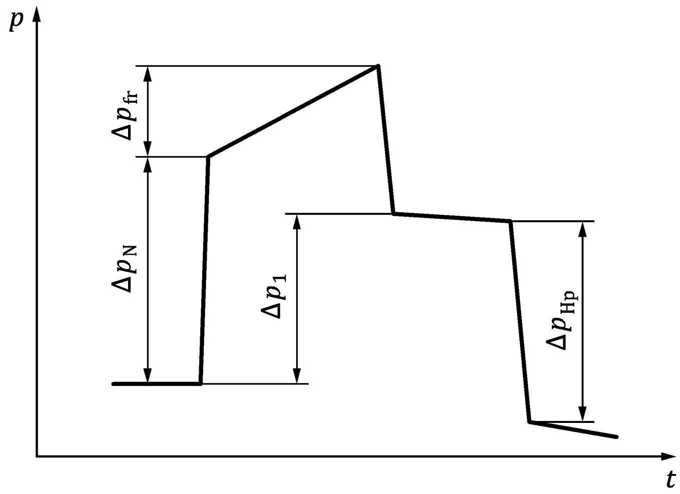

Figure A.1 — Calculation of a train-tunnel-pressure signature

A.3.2 Symbols

For the purposes of this annex, the following symbols apply:

$C_{\mathrm{f,tr}}$	friction coefficient of the train;
$C_{\mathrm{f,tu}}$	friction coefficient of the tunnel;
$C_{\mathrm{x,tu}}$	drag coefficient of the train in the tunnel;
L_{t}	tail length;
Pe_{tr}	train perimeter;

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[4] Sockel, [2].

Pe_{tu}	tunnel perimeter;
Δp_1	pressure after train tail entrance;
Δp_{fr}	pressure increase due to friction effects;
Δp_{N}	pressure increase caused by nose entrance of the train;
Δp_{HP}	nose passing pressure drop;
X_{d}	dummy variable;
X_{h}	dummy variable;
X_{fr}	dummy variable;
X_{t}	dummy variable;
ζ_{E}	loss coefficient for tunnel portal;
ζ_1	loss coefficient for the train;
ζ_{h}	loss coefficient of the train nose in the tunnel;
ζ_{h0}	loss coefficient of the train nose in the open air;
ζ_{h1}	coefficient for additional loss of the train nose in the tunnel;
ζ_{t}	loss coefficient of the train tail in the tunnel;
ζ_{t0}	loss coefficient of the train tail in the open air;
ζ_{t1}	coefficient for additional loss of the train tail in the tunnel.

A.3.3 Calculation of Δp_{N}

Δp_{N} can be calculated by solving the following nonlinear formula for X_{h}, which is the Mach number of the flow ahead of the train:

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$$X_{\mathrm{h}} + \frac{\left(\mathrm{Ma} - X_{\mathrm{h}}\right)^2 \left(1 + X_{\mathrm{h}}\right)}{2}\left[1 - \frac{1 + X_{\mathrm{h}}}{\left(1 - B\right)^2}\right] - \frac{\zeta_{\mathrm{h}}\left(\mathrm{Ma} - X_{\mathrm{h}}\right)^2 \left(1 + X_{\mathrm{h}}\right)^2}{2\left(1 - B\right)^2} = 0 \qquad \text{(A.9)}$$

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NOTE The formulation of Formulae (A.9) and (A.13) were adjusted as referenced in [2].

ζ_{h} takes into account friction effects and separation effects at the nose of the train.

$$\zeta_h = \zeta_{\mathrm{h0}} B + \zeta_{\mathrm{h1}} B^2 \qquad \text{(A.10)}$$

ζ_{h0} is the loss coefficient of the train nose in the open air. ζ_{h1} takes into account aerodynamic effects in the tunnel and may be taken 0 for aerodynamically well shaped trains. The reference static pressure p_0 can be taken as the ambient pressure.

$$\Delta p_{\mathrm{N}} = \left(\left[1 + \frac{\kappa - 1}{2} X_{\mathrm{h}}\right]^{\frac{2\kappa}{\kappa - 1}} - 1\right) p_0 \qquad \text{(A.11)}$$

A.3.4 Calculation of Δp_{fr}

$$\zeta_{\mathrm{fr}} = \frac{1}{S_{\mathrm{tu}} - S_{\mathrm{tr}}}\left(\left(\left(L_{\mathrm{tr}} - L_{\mathrm{n}} - L_{\mathrm{t}}\right) C_{\mathrm{f,tr}} Pe_{\mathrm{tr}}\right) - L_{\mathrm{tr}} C_{\mathrm{f,tu}} Pe_{\mathrm{tu}} \frac{\left(X_{\mathrm{fr}}\left(1 + X_{\mathrm{fr}}\right) - \left(X_{\mathrm{fr}} + B\right)\mathrm{Ma}\right) \times \left|X_{\mathrm{fr}}\left(1 + X_{\mathrm{fr}}\right) - \left(X_{\mathrm{fr}} + B\right)\mathrm{Ma}\right|}{\left(\mathrm{Ma} - X_{\mathrm{fr}}\right)^2 \left(1 + X_{\mathrm{fr}}\right)^2}\right) \quad \text{(A.12)}$$

Δp_{fr} can be calculated by solving the following Formula (A.13) for X_{fr}, where ζ_{fr} in this formula should be replaced by Formula (A.12). If X_{fr} in Formula (A.12) is replaced by X_{h} for simplifying the procedure, the result Δp_{fr} will be some percent higher.

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$$X_{\mathrm{fr}} + \frac{\left(\mathrm{Ma} - X_{\mathrm{fr}}\right)^2 \left(1 + X_{\mathrm{fr}}\right)}{2}\left[1 - \frac{1 + X_{\mathrm{fr}}}{\left(1 - B\right)^2}\right] - \left(\zeta_{\mathrm{h}} + \zeta_{\mathrm{fr}}\right)\frac{\left(\mathrm{Ma} - X_{\mathrm{fr}}\right)^2 \left(1 + X_{\mathrm{fr}}\right)^2}{2\left(1 - B\right)^2} = 0 \quad \text{(A.13)}$$

$$\Delta p_{\mathrm{fr}} = \left(\left[1 + \frac{\kappa - 1}{2} X_{\mathrm{fr}}\right]^{\frac{2\kappa}{\kappa - 1}} - 1\right) p_0 - \Delta p_{\mathrm{N}} \quad \text{(A.14)}$$ 〈AC

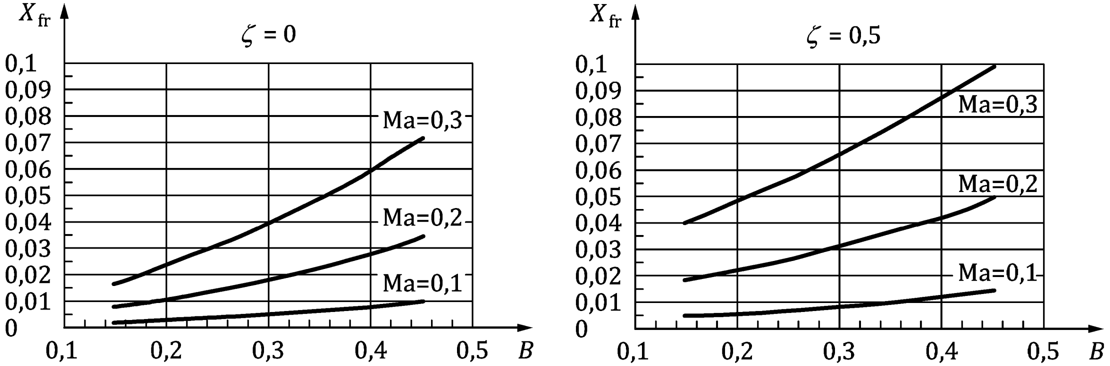


Figure A.2 — Solutions X_{fr} of Formula (A.13) for different values of $\zeta = \zeta_{\mathrm{h}} + \zeta_{\mathrm{fr}}$

A.3.5 Calculation of Δp_{T}

$$\zeta_{\mathrm{fr}} = \frac{1}{S_{\mathrm{tu}} - S_{\mathrm{tr}}} \left(\left(L_{\mathrm{tr}} - L_{\mathrm{n}} - L_{\mathrm{t}} \right) C_{\mathrm{f,tr}} Pe_{\mathrm{tr}} - L_{\mathrm{tr}} C_{\mathrm{f,tu}} Pe_{\mathrm{tu}} \frac{\left(X_{\mathrm{t}} \left(1 + X_{\mathrm{t}} \right) - \left(X_{\mathrm{t}} + B \right) \mathrm{Ma} \right) \times \left| X_{\mathrm{t}} \left(1 + X_{\mathrm{t}} \right) - \left(X_{\mathrm{t}} + B \right) \mathrm{Ma} \right|}{\left(\mathrm{Ma} - X_{\mathrm{t}} \right)^2 \left(1 + X_{\mathrm{t}} \right)^2} \right) \tag{A.15}$$

$$a = \left(\zeta_{\mathrm{h}} + \zeta_{\mathrm{fr}} + \zeta_{\mathrm{t}} \right) \kappa \frac{\left(\left(\mathrm{Ma} - X_{\mathrm{t}} \right)^2 \left(1 + \left(2 - \kappa \right) X_{\mathrm{t}} \right) \right)}{\left(1 - B \right)^2 \left(2 - \kappa \left(\mathrm{Ma} - X_{\mathrm{t}} \right)^2 \left(1 - \left(\kappa - 1 \right) X_{\mathrm{t}} \right) \right)} \tag{A.16}$$

where ζ_{t} takes into account friction effects at the tail of the train and wake effects behind the train.

$$\zeta_t = \zeta_{\mathrm{t0}} B + \zeta_{\mathrm{t1}} B^2 \tag{A.17}$$

ζ_{t0} is the loss coefficient of the train tail in the open air. ζ_{t1} takes into account aerodynamic effects in the tunnel and can be taken to be 0,6 for aerodynamically well shaped trains.

Δp_1 can be calculated by solving the following nonlinear formula for X_{t}, where a in this formula should be replaced by Formula (A.16).

$$\kappa X_t - a\left(1 + \kappa X_t \right) + \frac{\kappa \left(X_t - a \cdot \mathrm{Ma} \right)^2 \left(1 + \zeta_E \right)}{2\left(1 - a \right)^2} = 0 \tag{A.18}$$

ζ_{E} can be taken as 0,5.

$$\Delta p_1 = \left(\left[1 + \frac{\kappa - 1}{2} X_t \right]^{\frac{2\kappa}{\kappa - 1}} - 1 \right) p_0 \tag{A.19}$$

Δp_{T} is obtained as $\Delta p_{\mathrm{T}} = \Delta p_{\mathrm{N}} + \Delta p_{\mathrm{fr}} - \Delta p_1$.

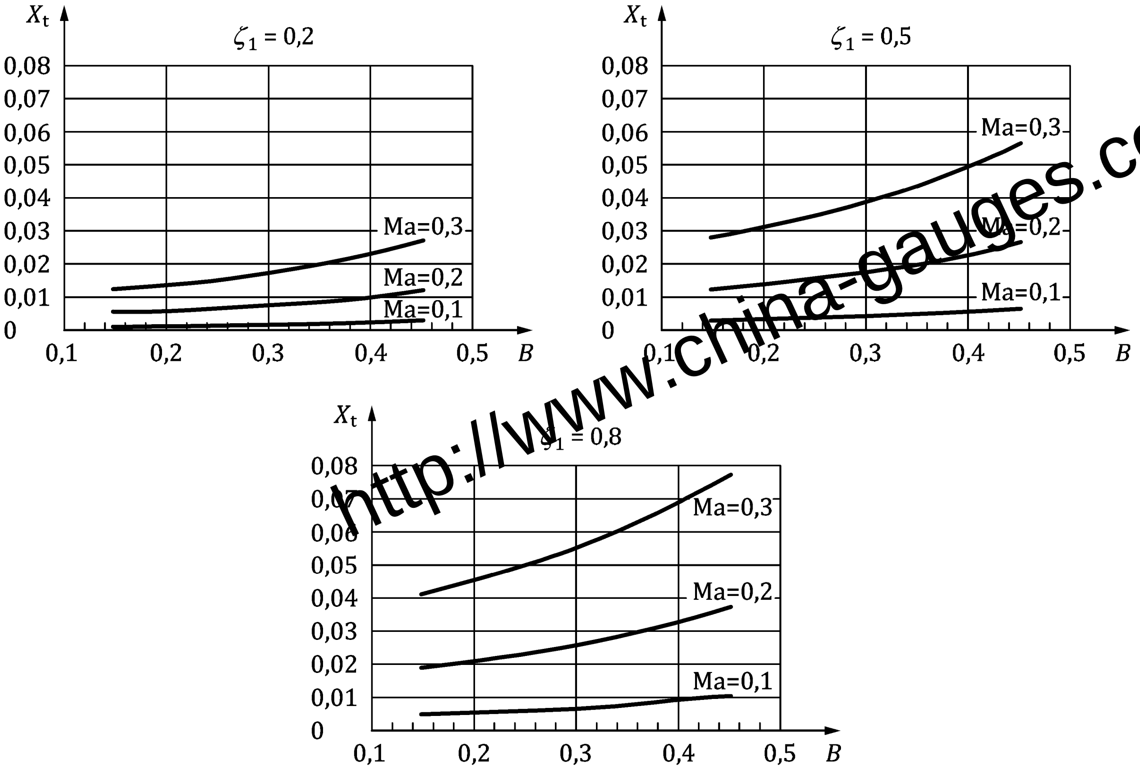


Figure A.3 — Solution X_t of Formula (A.18) for different values of $\zeta_1 = \zeta_h + \zeta_{fr} + \zeta_t$ with $\zeta_E = 0,5$

The nose passing pressure difference Δp_{HP} can be calculated with X_t, the solution of Formula (A.18) and the following formulae.

$$Y = \frac{1}{1+X_t}\left[1+\frac{\left(\mathrm{Ma}-X_t\right)^2}{2\left(1+\frac{\kappa-1}{2}X_t\right)^2}\left(\frac{1}{\left(1-B\right)^2}-1\right)\left(1+\frac{\left(\kappa+1\right)\left(\mathrm{Ma}-X_t\right)^2}{2\left(1+\frac{\kappa-1}{2}X_t\right)^2\left(1-B\right)^2}\right)\right] \tag{A.20}$$

$$\Delta p_{HP} = \left[\kappa\left(Y-1+X_t\right)+\frac{\kappa\zeta_h\left(\mathrm{Ma}-X_t\right)^2\left(1+X_t\right)^2}{\left(1-B\right)^2}\right]p_0 \tag{A.21}$$

A.3.6 Calculation of the drag coefficient $C_{x,tu}$

A.3.6.1 Method 1

The method should be applied for B > 0,05 only.

$$q = \frac{\mathrm{Ma}-X_t}{1-a} \tag{A.22}$$

a should be calculated with Formula (A.16).

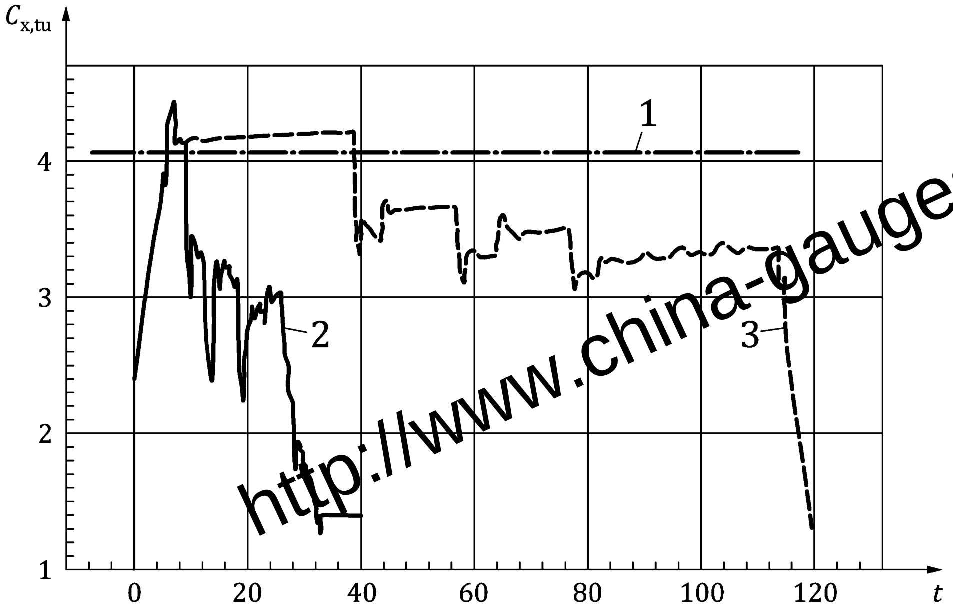
$$\mathrm{Ma}-w = \frac{X_t\left(1+X_t\right)-\mathrm{Ma}\left(B+X_t\right)}{1-B} \tag{A.23}$$

$$C_{\mathrm{x,tu}} = \frac{2}{\mathrm{Ma}^2 B}\left[\frac{\Delta p_1}{\kappa p_0} + \left(1+\zeta_E\right)\frac{\left(\mathrm{Ma}-q\right)^2}{2} + \left(\mathrm{Ma}-X_{\mathrm{t}}\right)^2\left(1+\frac{\Delta p_1}{p_0}\right)^{\frac{1}{\kappa}}\left(1-\frac{q}{\left(\mathrm{Ma}-X_{\mathrm{t}}\right)}\right) + BC_{\mathrm{f,tu}}Pe_{\mathrm{tu}}L_{\mathrm{tr}}\frac{\left(\mathrm{Ma}-w\right)\sqrt{\left(\mathrm{Ma}-w\right)^2}}{2S_{\mathrm{tr}}}\right] \quad \text{(A.24)}$$

$$F_{\mathrm{x}} = C_{\mathrm{x,tu}}\rho S_{\mathrm{tr}}\frac{v_{\mathrm{tr}}^2}{2} \quad \text{(A.25)}$$

This value is the aerodynamic drag just after the entrance of the tail of the train into the tunnel.

In Figure A.4 there is plotted the aerodynamic drag coefficient $C_{\mathrm{x,tu}}$ as a function of time for the passages of a train through a short tunnel (L_{tu} = 1 900 m) and a long tunnel (L_{tu} = 8 000 m), all other parameters being identical. The tail of the train enters the tunnel at approximately 8 s. For the short tunnel $C_{\mathrm{x,tu}}$ is constant for a very short time (solid line) for the long tunnel $C_{\mathrm{x,tu}}$ is nearly constant for a long time, but the values are equal for both cases. This value is given by Formula (A.24).



Key

1 predicted by method 2

	L_{tu}	B	Ma	S_{tu}	Pe_{tu}	L_{tr}	S_{tr}	Pe_{tr}	c_{tu}	c_{tr}	ζ_k
2	1 900 m	0,18	0,2	55,56 m²	30,6 m	400 m	10 m²	11 m	0,005	0,00 435	3,55
3	8 000 m	0,18	0,2	55,56 m²	30,6 m	400 m	10 m²	11 m	0,005	0,00 435	3,55

t time, in s

Figure A.4 — Aerodynamic drag coefficient

If the aerodynamic drag coefficient C_x for the open air is known, the tunnel factor is given by

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$$T_f = \frac{C_{x,tu}}{C_x} \tag{A.26}$$

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A.3.6.2 Method 2

The drag coefficient $C_{x,tu}$ for a train accelerated to steady train speed in the middle of the tunnel may be calculated with the assumption of incompressible flow over the train by solving the following formula for X_d

$$\frac{4X_d}{\mathrm{Ma}} - \frac{1}{\left(1-B\right)^2}\left[C_1 B\left(1-X_d\right)^2 - C_2\left(X_d - B\right)\sqrt{\left(X_d - B\right)^2}\right] = 0 \tag{A.27}$$

$$C_1 = B\left(\zeta_{h1} + \zeta_{t1}\right) + C_x + \frac{c_{f,tr} Pe_{tr}\left(L_{tr} - L_n - L_t\right)B}{S_{tr}\left(1-B\right)} \tag{A.28}$$

$$C_2 = \frac{c_{f,tu} Pe_{tu} L_{tr}}{S_{tu}\left(1-B\right)} \tag{A.29}$$

$$C_{\mathrm{x,tu}} = \frac{1}{\left(1-B\right)^2}\left[C_1\left(1-X_d\right)^2 - C_2\left(X_d-B\right)\sqrt{\left(X_d-B\right)^2}\right] \quad \text{(A.30)}$$

The tunnel factor is given by Formula (A.26).

A.4 GB approach, ignoring changes in air density and the speed of sound

A.4.1 General

In the GB approach, the air density and the speed of sound are treated as constants, and these formulae give satisfactory calculations of the pressure changes up to a train Mach number of 0,4. (References: see [19] and [20])

For the purposes of this annex the following symbols apply:

ζ_{N}	train nose pressure loss coefficient
ζ_{p}	tunnel portal pressure loss coefficient
ζ_{T}	train tail pressure loss coefficient
$C_{\mathrm{f,tr}}$	train Fanning friction factor
$C_{\mathrm{f,tu}}$	tunnel Fanning friction factor
Pe_{tr}	perimeter of train
Pe_{tu}	perimeter of tunnel
U_0	flow velocity in tunnel relative to train before train entry (NB for no flow in the tunnel, $U_0 = -v_{\mathrm{tr}}$
φ	area ratio (1-$S_{\mathrm{tr}}/S_{\mathrm{tu}}$)

A_1, A_2, A_3, B_1, B_2, B_3, C_1, C_2, C_3 are dummy functions

A.4.2 Calculation of Δp_{N}

$$\Delta p_N = \frac{-B_1 - \sqrt{B_1^2 - 4A_1C_1}}{2A_1} \quad \text{(A.31)}$$

where

$$A_1 = \frac{1}{\rho c^2} \quad \text{(A.32)}$$

$$B_1 = 2\left[\frac{U_0}{c} - \left(\frac{1}{\frac{\zeta_N+1}{\varnothing^2} - 1}\right)\right] \quad \text{(A.33)}$$

$$C_1 = \rho U_0^2 \quad \text{(A.34)}$$

A.4.3 Calculation of Δp_{fr}

$$\Delta p_{\mathrm{fr}} = \rho c \left(\Phi \left(\frac{-B_2 - \sqrt{{B_2}^2 - 4A_2C_2}}{2A_2} \right) - \mathrm{U}_0 \right) - \Delta p_{\mathrm{N}} \quad \text{(A.35)}$$

where

$$A_2 = \frac{1}{2}\left\{ L_{\mathrm{tr}} \left[\frac{C_{\mathrm{f,tr}}\mathrm{Pe}_{\mathrm{tr}} + C_{\mathrm{f,tu}}\mathrm{Pe}_{\mathrm{tu}}}{S_{\mathrm{tu}} - S_{\mathrm{tr}}} \right] + \zeta_{\mathrm{N}} + \left(1 - \Phi^2\right) \right\} \quad \text{(A.36)}$$

$$B_2 = \frac{C_{\mathrm{f,tu}}\mathrm{Pe}_{\mathrm{tu}} L_{\mathrm{tr}} v_{\mathrm{tr}}}{S_{\mathrm{tu}} - S_{\mathrm{tr}}} - c\Phi \quad \text{(A.37)}$$

$$C_2 = \frac{1}{2}\left\{ \frac{C_{f,\mathrm{tu}}\mathrm{Pe}_{\mathrm{tu}} L_{\mathrm{tr}} {v_{\mathrm{tr}}}^2}{S_{\mathrm{tu}} - S_{\mathrm{tr}}} \right\} + \mathrm{cU}_0 \quad \text{(A.38)}$$

A.4.4 Calculation of Δp_{T}

$$\Delta p_T = \rho c \left\{ \frac{-B_3 - \sqrt{{B_3}^2 - 4A_3C_3}}{2A_3} + \frac{B_2 + \sqrt{{B_2}^2 - 4A_2C_2}}{2A_2} \right\} \quad \text{(A.39)}$$

where

$$A_3 = \frac{1}{2}\left(\zeta_{\mathrm{T}} - \zeta_p \phi^2 - 1 \right) \quad \text{(A.40)}$$

$$B_3 = -\left[c + v_{\mathrm{tr}}\, \phi \left(1 + \zeta_{\mathrm{p}} \right) \right] \quad \text{(A.41)}$$

$$C_3 = -\frac{{v_{\mathrm{tr}}}^2}{2} \left\{ \left(1 + \zeta_{\mathrm{p}} \right) - c \left[\frac{B_2 + \sqrt{B_2^2 - 4A_2C_2}}{2A_2} \right] \right\} \quad \text{(A.42)}$$

Annex B
(informative)

Pressure comfort criteria

B.1 General

The European Rail Research Institute (ERRI) suggests the following basic comfort criteria.[5]

NOTE The values mentioned in B.2 and B.3 cannot be imposed as a requirement on rolling stock. They could be used in assessment of pressure comfort for a given train operation in tunnels to be specified.

B.2 Unsealed trains (generally $\tau_{\mathrm{dyn}} < 0{,}5$ s)[6]

The pressure experienced by a passenger on board a train should not exceed a change of:

- 4 500 Pa within a period of 4 s for the worst case involving two trains passing in a double-track tunnel in a critical crossing situation;
- 3 000 Pa within a period of 4 s for a single-track tunnel.

The limit for a single train in a single-track tunnel is less (i.e. more stringent) than for the two train case in a double-track tunnel due to the fact that the same pressures will occur in that tunnel every time that train passes through that same tunnel at that same speed. Therefore, in effect, the worst case pressures for that train can occur every time. For the two trains/double-track tunnel situation, the occurrence of the worst (critical) case pressures is less frequent because it requires not only both trains to be passing through at the same time but also for them to pass at a particular position within the tunnel. A raised limit can therefore be allowed due to the lower statistical probability of this critical event occurring.

B.3 Sealed trains (generally $\tau_{\mathrm{dyn}} > 0{,}5$ s)

The pressure experienced by a passenger on board a train should not exceed a change of:

- 1 000 Pa within a period of 1 s;
- 1 600 Pa within a period of 4 s;
- 2 000 Pa within a period of 10 s.

This criterion applies to the single-track tunnel case and to the case involving two trains passing in a double-track tunnel in a critical crossing situation.

As the degree of sealing is increased, it is the pressure change occurring over longer time intervals that becomes increasingly important for comfort.

NOTE Typical values τ_{dyn} of sealed trains are in a range of 4 s to 20 s.

---

[5] ERRI C 218, [4].

[6] τ_{dyn} is the time constant characterising the pressure tightness of a moving rail vehicle, see 7.8 for details.

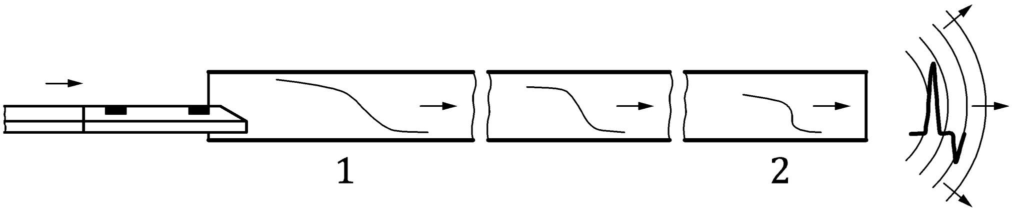
Annex C
(informative)

Micro-pressure wave

C.1 General

When the nose of a train enters a tunnel, a compression wave is generated which propagates through the tunnel at the speed of sound. At the exit portal the majority of this ”compression wave” reflects as an expansion wave and propagates back towards the entry portal. A smaller part of the compression wave” exits the tunnel and radiates outside, in the form of an impulse-like micro-pressure wave (see Figure C.1).

The micro-pressure wave can create a booming noise and may lead to the rattling of structures like windows, doors etc. and causes noise pollution in a wide area around the tunnel exit.



Key

1 tunnel entrance portal (entry)
2 tunnel exit portal (exit)

Figure C.1 — Wave generation, propagation and radiation

C.2 Compression wave generation

The pressure gradient at the entry portal can be:

- measured in full-scale tests, or
- calculated with three dimensional numerical tools, or
- measured with moving model tests, or
- roughly estimated for streamlined noses and simple tunnel portals without hoods, flares, etc. by the following formulae:

$$\left(\frac{\partial p}{\partial t}\right)_{entry} = \frac{\Delta p_N}{\Delta t} \qquad \text{(C.1)}$$

$$\Delta t = C_n \frac{L_n}{v_{\mathrm{tr}}} \qquad \text{(C.2)}$$

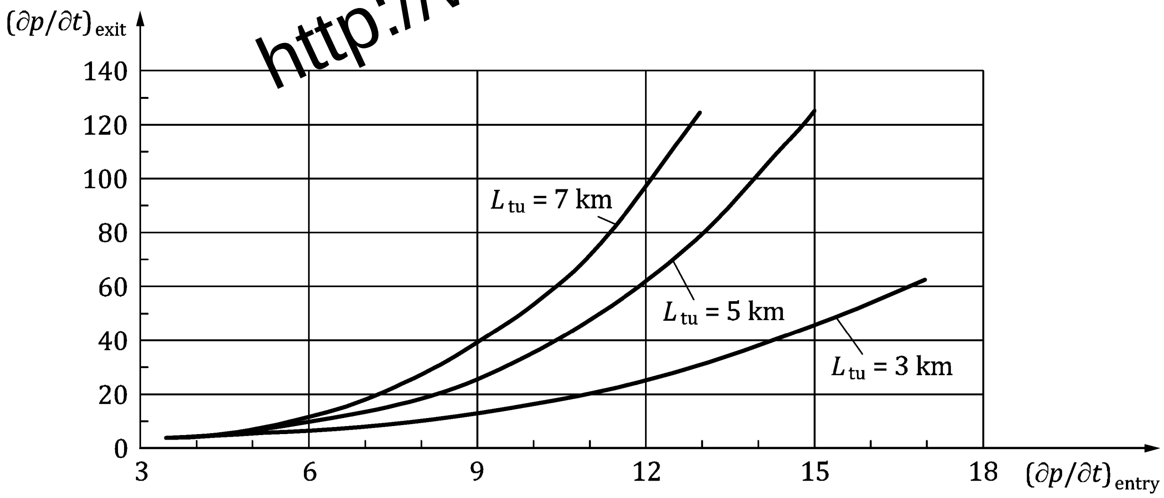
NOTE Wave generation and the parameter maximum entry pressure gradient are the interface between rolling stock and infrastructure as described in 5.2 and 6.2.

C.3 Compression wave propagation

Depending on the initial gradient of the compression wave, steepening may lead to much greater gradients at the exit portal if the tunnel is fitted with modern concrete slab track, which provides little dissipation to the propagating wave. In ballasted track tunnels, the gradient at the exit portal is smaller than at the entry portal.

The steepening can be:

- measured in full-scale tests, or
- calculated with numerical tools, or
- estimated by using Figure C.2.



Key

$(\partial p/\partial t)_{\text{exit}}$	exit gradient, in kPa/s
$(\partial p/\partial t)_{\text{entry}}$	entry gradient, in kPa/s

Figure C.2 — Steepening in concrete slab tunnels

C.4 Micro-pressure wave radiation

The radiated micro-pressure pulse can be:

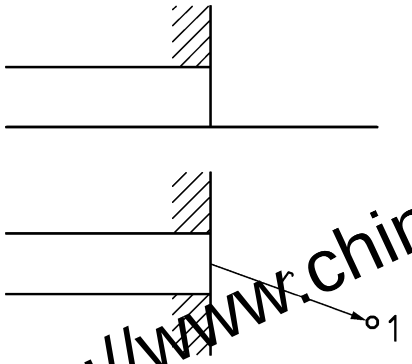
- measured in full-scale tests, or
- calculated with numerical tools, or
- measured in model tests, or
- roughly estimated for simple tunnel exit portals using[7]:

$$\Delta p\left(r,t\right)=\frac{2A_{\text{tu}}}{\Omega cr}\left(\frac{dp}{dt}\right)_{\text{exit}} \tag{C.3}$$

---

[7] Herb et al., [6].

Where r (radius) is the distance between tunnel exit portal centre (on the ground) and the point of interest (reception point, outside of tunnel) (see Figure C.3).



Key

1 reception point

Figure C.3 — Radiation of micro-pressure wave

Values for Ω are typically in the range of 2 to 4.

The limits for the application of the above formula are:

$$\left(\frac{\mathrm{dp}}{\mathrm{dt}}\right)_{\mathrm{exit}} \le \frac{\Delta p_{\mathrm{exit}}\, c}{\sqrt{\frac{32A_{\mathrm{tu}}}{\pi}}} \tag{C.4}$$

and

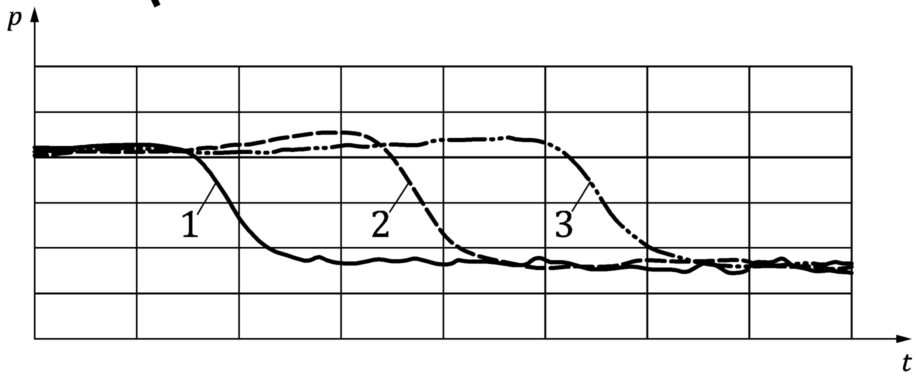
$$r > \sqrt{\frac{2A_{\mathrm{tu}}}{\pi}} \tag{C.5}$$

Annex D
(informative)

Pressure loading on unsealed crossing trains

When the nose of a train passes another train, a pressure drop occurs which travels with the relative speed of the trains (see Figure D.1) along the passed train. A pressure increase occurs when the tail passes. The gradient of these pressure changes may be much steeper than the gradients of the train-induced pressure waves. Due to this steepness, these pressure changes may lead to the loading of unsealed vehicles.

NOTE Unsealed trains can be passenger trains or specific enclosed freight vehicles. The diagrams provided in this annex are based on tests with sliding door freight vehicles.

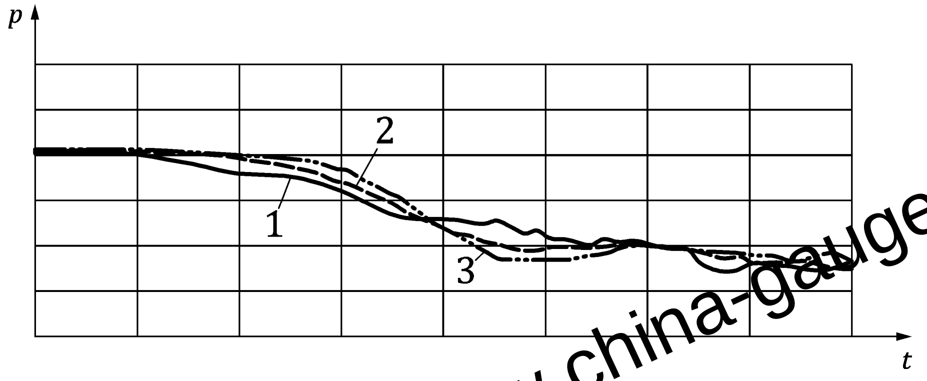


Key

1 external pressure at the front
2 external pressure in the middle
3 external pressure at the rear

Figure D.1 — External pressure drop due to the nose passage of a crossing train

When the nose of the opposing train passes the front of the unsealed vehicle, the internal pressure starts to decrease too. As the information about the pressure drop travels at the speed of sound inside the vehicle, the internal pressure is nearly independent of the location inside the vehicle (see Figure D.2).



Key

1 internal pressure at the front

2 internal pressure in the middle

3 internal pressure at the rear

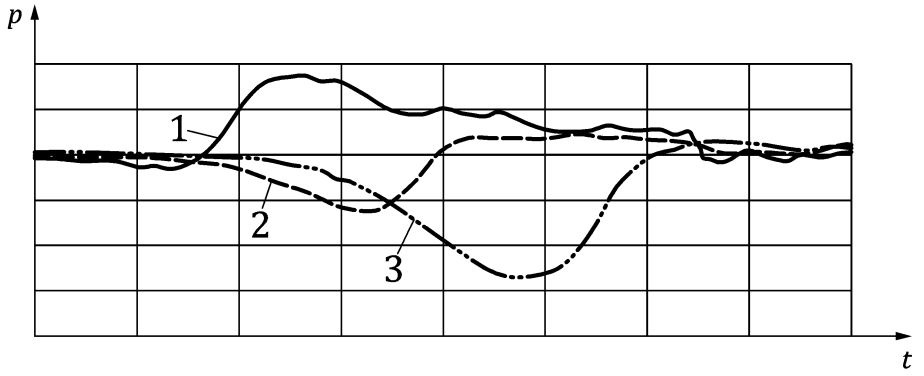
Figure D.2 — Internal pressure evolution inside an unsealed vehicle due to the nose passage of a crossing train

Figure D.3 shows the differences between the internal and external pressures at locations at the front, in the middle and at the rear of an unsealed vehicle during the nose passage of a crossing train.

At the front, both external and internal pressure drops start at the same time. Due to the steeper gradient of the external pressure drop, the pressure difference generates a load from the inside to the outside, which may be important for doors opening to the outside.

In the middle of the unsealed vehicle, the drop of the internal pressure starts earlier than the external pressure drop, which has a steeper gradient. This initially leads to a pressure difference directed from the outside to the inside, which then changes its direction.

At the rear end of the unsealed vehicle, the drop of the internal pressure starts earlier than the external pressure drop. The resulting pressure difference generates a load from the outside to the inside, which may be important for vehicles, such as swap bodies, covered with canvas or similar frangible materials.



Key

1 pressure difference at the front

2 pressure difference in the middle

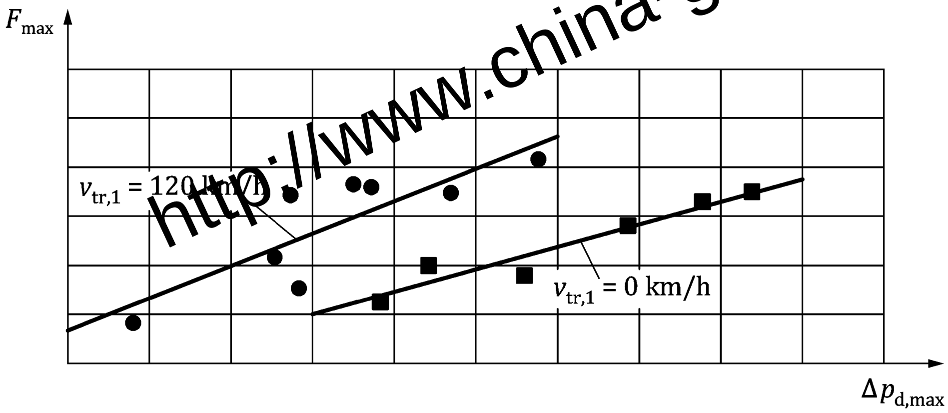
3 pressure difference at the rear

Figure D.3 — Pressure differences on an unsealed vehicle due to the nose passage of a crossing train (pi-pe)

The time that the nose of the crossing train takes to travel along an adjacent vehicle is

$$\Delta t = \frac{L_{\mathrm{veh}}}{v_{\mathrm{tr},1} + v_{\mathrm{tr},2}} \tag{D.1}$$

This means that for the case of a moving vehicle the time for the nose passing becomes shorter. The resulting mechanical forces may be higher, because of lateral accelerations, three-dimensional and inertial effects, as shown in Figure D.4.



Key

F_{max}	maximum measured force on the door
$\Delta p_{\mathrm{d,max}}$	maximum difference between internal and external pressures

NOTE Each point represents a different passing train speed $v_{\mathrm{tr},2}$.

Figure D.4 — Typical measured maximum forces on an unsealed vehicle door during the nose passage of a crossing train

Annex E
(informative)

Validation cases for the assessment of aerodynamic loads

E.1 General

This annex provides validation cases for the assessment of aerodynamic loads, see 7.7.

E.2 Validation procedure

Following steps are suggested for validation:

1) Use of the measurement data of ICE3 in the rainflow analysis according to 7.7.4.4 and comparison of damage-equivalent amplitudes with the given values according to Table E.1;

2) Comparison of simulated and measured pressure signatures for the four scenarios (no quantitative criteria, graphical comparison) and definition of appropriate parameters for the train ICE3 and the tunnel;

3) Use of simulated data for ICE3 in the rainflow analysis according to 7.7.4.4 and comparison of damage-equivalent amplitudes with the given values according to Table E.1.

To validate the procedure, the four scenarios in Table E.1 should be used. For every scenario the simulated pressure should be compared to the measured one. The simulated pressure signals should be assessed with the method according to 7.7.4. The damage-equivalent amplitude should be compared to Table E.1. The values in Table E.1 refer to an unclassified rainflow matrix. The assessment procedure should be considered as validated if the computed damage equivalent amplitudes are within −10 % to +30 % of the documented values. A damage-equivalent amplitude from a single tunnel passing as denoted in Table E.1, is referring to the reference cycles $N_c = 1000$ for demonstration only.

The measured pressure signals are available free of charge in electronic form at the TC 256 Secretariat held by DIN FSF.

Table E.1 — Parameters for scenarios for tunnel operations

Scenario	Unit	Solo1	Solo2	Cross1	Cross2
Train 1	-	ICE3 DT (400 m)	ICE3 DT (400 m)	ICE3 DT (400 m)	ICE3 DT (400 m)
Train 2	-	-	-	ICE3 DT (400 m)	ICE3 DT (400 m)
$v_{\mathrm{tr},1}$	m/s	75,9	76,8	76,1	77,9
$v_{\mathrm{tr},2}$	m/s	-	-	83,6	83,3
Δt_{e}	s	-	-	11,4	13,2
Temperature	°C	11,4	13,2	14,0	13,6
Atmospheric Pressure p_{atm}	hPa	975,8	974,8	974,3	973,1
Relative humidity H	%	47,1	43,0	41,9	34,0
Tunnel	-	Fernthaltunnel	Fernthaltunnel	Fernthaltunnel	Fernthaltunnel
Length	m	1 555	1 555	1 555	1 555
Cross section	m^2	92	92	92	92
Sensor position X_{p}	m	1 140	1 140	1 140	1 140
Total simulation time	s	120	120	120	120
Reference cycles NC	-	1 000	1 000	1 000	1 000
S-N curve exponent k	-	3	3	3	3
Damage-equivalent amplitude p_{eq}	Pa	201,9	219,7	447,3	332,9

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