BS EN 14067-4:2013

BSI Standards Publication

Railway applications — Aerodynamics

Part 4: Requirements and test procedures for aerodynamics on open track

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National foreword

This British Standard is the UK implementation of EN 14067-4:2013. It supersedes BS EN 14067-4:2005+A1:2009 and BS EN 14067-2:2002, which are withdrawn.

The UK committee draws users' attention to the distinction between normative and informative elements, as defined in Clause 3 of the CEN/CENELEC Internal Regulations, Part 3.

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When rounded values require unit conversion for use in the UK, users are advised to use equivalent values rounded to the nearest whole number. The use of absolute values for converted units should be avoided in these cases. For the values used in this standard:

1 km/h has an equivalent value of 0.5 mile/h
20 km/h has an equivalent value of 10 mile/h
160 km/h has an equivalent value of 100 mile/h
200 km/h has an equivalent value of 125 mile/h
250 km/h has an equivalent value of 155 mile/h
300 km/h has an equivalent value of 190 mile/h

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A list of organizations represented on this subcommittee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

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This European Standard was approved by CEN on 21 September 2013.

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Foreword

This document (EN 14067-4:2013) 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of an identical text or by endorsement, at the latest by April 2014, and conflicting national standards shall be withdrawn at the latest by April 2014.

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

This document supersedes EN 14067-4:2005+A1:2009 and EN 14067-2:2003. The results of the EU-funded research project "AeroTRAIN" (Grant Agreement No. 233985) have been used.

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

EN 14067-2 has been integrated in this document, and EN 14067-4 has been re-structured and extended to support the Technical Specifications for the Interoperability of the Trans-European rail system and requirements on conformity assessment for rolling stock were added.

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

— *Part 1: Symbols and units*

— *Part 2: Aerodynamics on open track (to be withdrawn)*

— *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*

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Introduction

Trains running on open track generate aerodynamic loads on objects and persons they pass. If trains are being passed by other trains, trains are also subject to aerodynamic loading themselves. The aerodynamic loading caused by a train passing an object or a person near the track, or when two trains pass each other, is an important interface parameter between the subsystems of rolling stock, infrastructure and operation and, thus, is subject to regulation when specifying the trans-European railway system.

Trains running on open track have to overcome a resistance to motion which has a strong effect on the required engine power, achievable speed, travel time and energy consumption. Thus, resistance to motion is often subject to contractual agreements and requires standardized test and assessment methods.

1 Scope

This European Standard deals with requirements, test procedures and conformity assessment for aerodynamics on open track. Addressed within this standard are the topics of aerodynamic loadings and resistance to motion, while the topic of cross wind assessment is addressed by EN 14067-6.

This European Standard refers to rolling stock and infrastructure issues. This standard does not apply to freight wagons. It applies to railway operation on gauges GA, GB and GC according to EN 15273. The methodological approach of the presented test procedures may be adapted to different gauges.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 1991-2, *Eurocode 1: Actions on structures — Part 2: Traffic loads on bridges*

EN 15273 (all parts), *Railway applications — Gauges*

EN 15663, *Railway applications — Definition of vehicle reference masses*

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

3 Terms, definitions and symbols

3.1 Terms and definitions

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

3.1.1
peak-to-peak pressure change
modulus of the difference between the maximum pressure and the minimum pressure for the relevant load case

3.1.2
passage of train head
passage of the front end of the leading vehicle which is responsible for the generation of the characteristic pressure rise and drop, over and beside, the train and on the track bed

3.1.3
Computational Fluid Dynamics
CFD
numerical methods of approximating and solving the equations of fluid dynamics

3.1.4
streamline shaped vehicle
vehicle with a closed and smooth front which does not cause flow separations in the mean flow field greater than 5 cm from the side of the vehicle

3.1.5
bluff shaped vehicle
vehicle that is not streamlined

3.2 Symbols

For the purposes of this document, the following symbols apply.

Table 1 — Symbols

Symbol	**Unit**	**Significance**	**Explanation or remark**
b	m	reference length	train width
c	m/s	speed of sound	
C_F	–	coefficient of aerodynamic force	
C_{p1}	–	aerodynamic coefficient depending on the distance from track centre Y	
C_{p2}	–	aerodynamic coefficient depending on the height above top of rail h	
C_{p3}	–	aerodynamic coefficient depending on the distance from track centre Y	
C_1	N	rolling mechanical resistance	
$C_2\, v_{tr}$	N	momentum drag due to air flow for traction and auxiliary equipment and the air conditioning systems	
$C_3\, v_{tr}^2$	N	aerodynamic drag in the resistance to motion formula	
$d\, t$	s	temporal variation	
$d\, v_{tr}$	m/s	train speed variation	
$d\, x$	m	spatial variation	
F	N	load on an object, maximum value of the force during the passage	
g	m/s^2	acceleration due to gravity	
h	m	height above top of rail	
i	‰	gradient of the track	
k	–	factor accounting for the energy stored in rotating masses	≥ 1,0
k_1	–	shape coefficient of the train	
k_2	–	shape coefficient of the train	
k_3	–	shape coefficient of the train	
L_n	m	length of the train nose	distance from front end to where the full cross section of the leading vehicle is achieved
m	kg	train mass	normal operational payload according to EN 15663

Table 1 *(2 of 4)*

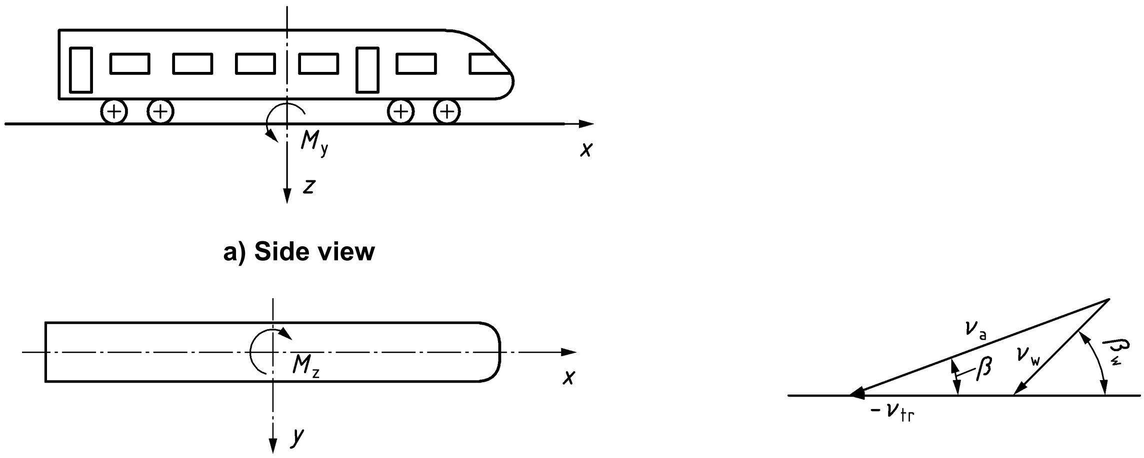
Symbol	**Unit**	**Significance**	**Explanation or remark**
p	Pa	pressure	
p_{max}	Pa	maximum pressure	
p_{min}	Pa	minimum pressure	
p_{1k}	Pa	characteristic value of distributed load	
p_{2k}	Pa	characteristic value of distributed load	
p_{3k}	Pa	characteristic value of distributed load	
r	m	curve radius	
Re	–	Reynolds number	based on reference length of 3,00 m at full scale
Re_{max}	–	maximum Reynolds number	
R_1	N	resistance to motion	train contribution
R_2	N	resistance to motion	infrastructure contribution
S	m^2	characteristic area	
t	s	time	
u_{i}	m/s	resultant horizontal air speed of the i-th passage	after transformation of the time base
$u_{\text{m,i}}$	m/s	measured resultant horizontal air speed of the i-th passage	
U	m/s	induced flow speed	
$\overline{U}$	m/s	mean value over all measured maxima U_{i}	
U_{i}	m/s	maximum resultant horizontal air speed of the i-th passage after averaging and correction to the characteristic train speed	
U_{max}	m/s	maximum value of U	
$U_{2\sigma}$	m/s	upper bound of a 2 σ interval of maximum air speed	
$U_{95\%}$	m/s	maximum resultant horizontal air speed	characteristic air speed
$U_{95\%,\text{max}}$	m/s	permissible maximum resultant horizontal air speed	permissible characteristic air speed
v_{tr}	m/s	train speed	
$v_{\text{tr,c}}$	m/s	full scale train speed	
$v_{\text{tr,i}}$	m/s	train speed during the i-th passage	
$v_{\text{tr,max}}$	m/s	maximum train speed	
$v_{\text{tr,ref}}$	m/s	reference speed	
$v_{\text{tr,test}}$	m/s	nominal test speed	

Table 1 *(3 of 4)*

Symbol	Unit	Significance	Explanation or remark
$v_{w,x,i}$	m/s	wind speed component in x-direction during the i-th passage	
y^+	–	dimensionless wall distance	
Y	m	lateral distance from track centre	
Y_{min}	m	minimum lateral distance from track centre	
Y_{max}	m	maximum lateral distance from track centre	
γ	m/s^2	train acceleration measured during the coasting test	
$\Delta C_{p,2\sigma}$	–	pressure change coefficient	Upper bound of a 2 σ interval of the peak-to-peak pressure change coefficient. The peak-to-peak pressure change coefficient is defined in Formula 2.
ΔC_p	–	pressure change coefficient	
Δp	Pa	peak-to-peak pressure change	
$\overline{\Delta p}$	Pa	mean value for peak-to-peak pressure change	determined over all measurements Δp_i or by CFD
$\Delta p_{2\sigma}$	Pa	upper bound of a 2 σ interval of the peak-to-peak pressure change	
$\Delta p_{95\%}$	Pa	maximum peak-to-peak pressure change	characteristic pressure change
$\Delta p_{95\%,max}$	Pa	permissible maximum peak-to-peak pressure change	permissible characteristic pressure change
Δp_i	Pa	maximum peak-to-peak pressure value of the i-th passage	
$\Delta p_{m,i}$	Pa	maximum peak-to-peak pressure value measured during the i-th passage	
Δp_{sim}		the head pressure variation from unsteady CFD calculations	
$\overline{\Delta p_{sim}}$	Pa	the head pressure variation from steady CFD calculations	
Δt	s	characteristic time interval	passage of train head, time between pressure peaks
ε	-	relative difference	
$\sum R_i$	N	sum of all the resistances to motion	
η	Pa·s	dynamic viscosity	
ρ	kg/m^3	air density	
ρ_i	kg/m^3	air density determined during the i-th passage	
ρ_0	kg/m^3	standard air density	ρ_0 = 1,225 kg/m^3

Table1 *(4 of 4)*

Symbol	Unit	Significance	Explanation or remark
σ	–	standard deviation	can be pressure or speed
σ_{sim}	Pa	standard deviation of simulated pressure	



a) Side view

b) Top view

c) Speed vector diagram

Figure 1 – Coordinate system

4 Requirements on locomotives and passenger rolling stock

4.1 Limitation of pressure variations beside the track

4.1.1 General

A passing train generates a varying pressure field beside the track which has an effect on objects such as crossing trains, noise barriers, platform installations, etc. To define a clear interface between the subsystems of rolling stock and infrastructure, the train-induced aerodynamic pressure loads beside the track need to be known and limited.

In order to describe and to limit the train-induced aerodynamic pressure loads beside the track one reference case for rolling stock assessment is defined.

4.1.2 Requirements

4.1.2.1 Reference case

For standard GA, GB, GC gauge according to EN 15273 in the absence of embankments, cuttings and other significant trackside structures the undisturbed pressure field generated by a passing train at a position of 2,50 m distance from the centre of a straight track with standard track formation profile is referred to as the reference case. The pressure variations occurring are characterized by the upper bound of the 95 % confidence interval for the maximum peak-to-peak pressure. This maximum peak-to-peak pressure change, $\Delta p_{95\%}$, refers to the maximum pressure change which occurs during the passage of the train head.

4.1.2.2 Fixed or pre-defined train compositions

A fixed or pre-defined train composition, running at the reference speed in the reference case scenario shall not cause the maximum peak-to-peak pressure changes to exceed a value $\Delta p_{95\%,max}$ as set out in Table 2 over the range of heights 1,50 m to 3,00 m above the top of rail during the passage of the train head. For non-identical end cars the requirement applies for each possible running direction.

Table 2 — Maximum permissible peak-to-peak pressure change $\Delta p_{95\%,max}$ depending on maximum design speed

Maximum design speed	Permissible pressure change $\Delta p_{95\%,max}$ at reference speed	Reference speed
$v_{tr} \leq 160$ km/h	no requirement	
160 km/h < v_{tr} < 250 km/h	$\Delta p_{95\%,max}$ = 800 Pa	maximum design speed
250 km/h ≤ v_{tr}	$\Delta p_{95\%,max}$ = 800 Pa	250 km/h

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

Single rolling stock units fitted with a driver's cab running as the leading vehicle at the reference speed in the reference case scenario shall not cause the maximum peak-to-peak pressure changes to exceed a value $\Delta p_{95\%,max}$ as set out in Table 2. The range of heights to be considered are 1,50 m to 3,00 m above the top of rail during the passage of the front end of this unit. For single rolling stock units capable of bidirectional operation as a leading vehicle the requirement applies for each possible running direction.

4.1.2.4 Other passenger rolling stock

For passenger rolling stock which is not covered in 4.1.2.2 or 4.1.2.3 there is no requirement.

4.1.3 Full conformity assessment

A full conformity assessment of interoperable rolling stock shall be undertaken according to Table 3.

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

Maximum design speed	Methods
$v_{tr} \leq 160$ km/h	No assessment needed
160 km/h < v_{tr}	Assessment by: — full-scale tests according to 6.1.2.1; or — reduced-scale moving model tests according to 6.1.2.2; or — CFD simulations according to 6.1.2.4.

4.1.4 Simplified conformity assessment

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

With respect to pressure variations beside the track, the only relevant design differences are differences in external geometry and differences in design speed.

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

— a statement and rationale that the design differences have no impact on the pressure variations beside the track;

— 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 — locations either downstream of the distance of the maximum cross-section from the train nose or downstream of the distance of the minimum pressure peak relative to the train nose, — the inner region of the underpart of the train (under the train and between rails), — minor differences in external geometry, — wipers and handles, — antennae with a volume smaller than 5 l, — long isolated protruding objects or gaps not being vertical or close to the front-side radius or edge smaller than 50 mm in the crosswise dimensions, — small isolated protruding objects and gaps smaller than 50 mm in each dimension.	Documentation of differences, statement of no impact and reference to an existing compliant full conformity assessment.
Other differences in external geometry (e.g. in buffers, front couplers, snow ploughs, front or side windows) keeping the basic head shape features.	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 6.1.2.2 or — CFD-simulations according to 6.1.2.4, AND evidence and documentation that (i) the difference causes changes in $\overline{\Delta p}$ less than ± 10 %, $\frac{\overline{\Delta p}(B)-\overline{\Delta p}(A)}{\overline{\Delta p}(A)} < 0{,}1$ NOTE B refers to the new train geometry. A refers to the existing compliant train. and (ii) the difference does not exceed 50 % of the margin available on the compliance with 4.1.2. $(\overline{\Delta p}(B)-\overline{\Delta p}(A)) < 0{,}5 \cdot (\Delta p_{95\%,\max} - \Delta p_{95\%}(A))$
Increase of design speed — less than 10 % for a train with original design speed < 250 km/h, — for a train with original design speed ≥ 250 km/h.	Documentation of differences and reference to an existing compliant full conformity assessment AND evidence and documentation based on a ΔC_p analysis that the new design under investigation still fulfils the requirements listed in 4.1.2.

4.2 Limitation of slipstream effects beside the track

4.2.1 General

A train generates a varying flow field beside the track which has an effect on persons and objects at the track side and at platforms. In order to define a clear interface between the subsystems of the rolling stock and the infrastructure, the train-induced slipstream effects need to be known and limited.

In order to describe and to limit the train-induced slipstream effects, a reference case for rolling stock assessment is defined.

NOTE Ensuring track workers' and passengers' safety at the platform involves additional issues on the operational and infrastructure side.

4.2.2 Requirements

4.2.2.1 Reference case

For standard GA, GB, GC gauges according to EN 15273, in the absence of embankments, cuttings and any significant trackside structures, the undisturbed flowfield generated by a passing train at a position of 3,00 m from the centre of a straight track with standard track formation profile is referred to as the reference case.

The air flows occurring are characterized by the upper bound of the 95 % confidence interval of maximum resultant horizontal air speeds. This maximum horizontal air speed $U_{95\%}$ refers to the whole passage of the train and its wake.

4.2.2.2 Fixed or pre-defined train compositions

A full-length, fixed or pre-defined train composition, running at reference speed in the reference case scenario shall not cause the maximum resultant horizontal air speed to exceed a value $U_{95\%,\text{max}}$ as set out in Table 5 at a height of 0,20 m above the top of rail during the passage of the whole train and its wake. For non-symmetrical train compositions, the requirement applies for each possible running direction. For fixed or pre-defined train compositions consisting of more than one train unit, it is sufficient to assess a train composition consisting at least of two units and of a minimum length of 120 m.

Table 5 — Maximum resultant permissible horizontal air speed $U_{95\%,\text{max}}$ depending on maximum design speed

Maximum design speed $v_{\text{tr,max}}$	**Height above the track**	**Permissible horizontal air speed $U_{95\%,\text{max}}$ at reference speed**	**Reference speed $v_{\text{tr,ref}}$**
$v_{\text{tr,max}} \leq 160$ km/h	no requirement		
160 km/h < $v_{\text{tr,max}}$ < 250 km/h	0,2 m	$U_{95\%,\text{max}} = 20$ m/s	the maximum design speed
	1,4 m	$U_{95\%,\text{max}} = 15{,}5$ m/s	200 km/h or the maximum design speed, whichever is lower
250 km/h ≤ $v_{\text{tr,max}}$	0,2 m	$U_{95\%,\text{max}} = 22$ m/s	300 km/h or, if lower, at maximum design speed
	1,4 m	$U_{95\%,\text{max}} = 15{,}5$ m/s	200 km/h

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

A single unit fitted with a driver's cab running at reference speed in the reference case scenario shall not cause the maximum resultant horizontal air speed to exceed a value $U_{95\%,\max}$ as set out in Table 5 at heights of 0,20 m and 1,40 m above the top of rail during the passage of the whole train and its wake.

Conformity shall be assessed for units at the front and rear of a rake of passenger carriages of at least 100 m in length. Assessments 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.

The requirement applies for each possible running direction.

4.2.2.4 Other passenger rolling stock

Carriages that are operated within trains of different formations are compliant, if similar to existing or proven compliant single rolling stock with respect to:

— design speed (lower or equal to existing); and

— bogie external arrangement (position, cavity and bogie envelope); and

— train envelope (i.e. body width, height) changes above the bogies of less than 10 cm.

The similarity and compliance for this approach shall be documented!

If this criterion does not apply, the coach running at reference speed in the reference case scenario shall not cause the maximum resultant horizontal air speed to exceed a value $U_{95\%,\max}$ as set out in Table 5 at heights of 0,20 m and 1,40 m above the top of rail during the passage of the whole train and its wake. It should be tested in two configurations with the rolling stock likely to be used in operation; positioned directly behind an existing or proven compliant locomotive with a rake of carriages of at least 100 m in length behind it, and at the rear of a rake of carriages at least 100 m in length behind a compliant locomotive. If the coach has a dedicated purpose, e.g. restaurant car, which will dictate its position to be always mid-train, it should be tested only in the middle of a rake of carriages at least 100 m long.

4.2.3 Full conformity assessment

A full conformity assessment of rolling stock shall be undertaken according to Table 6.

Table 6 — Methods applicable for full conformity assessment of rolling stock

Maximum design speed	Methods
$v_{tr} \leq 160$ km/h	no assessment needed
160 km/h < v_{tr}	assessment by full-scale tests according to 6.2.2.1 or documentation of compliance according to 4.2.2.4

4.2.4 Simplified conformity assessment

A simplified conformity assessment may be carried out for rolling stock which are subject to minor design differences in comparison to rolling stock for which a full conformity assessment already exists.

For a train composition that has been fully assessed for one direction of running, a simplified conformity assessment may be used for the other direction of running based on the full assessment.

With respect to resultant horizontal air speeds beside the track, the only relevant design differences are differences in external geometry and differences in design speed.

This simplified conformity assessment shall take one of the following forms in accordance with Table 7:

- a statement and rationale that the design differences have no impact on the resultant horizontal air speeds beside the track;
- a comparative evaluation of the design differences relevant to the rolling stock for which a full conformity assessment already exists.

Table 7 — Methods and requirements applicable for simplified conformity assessment of rolling stock

Design differences	Method / Requirement
Differences in external geometry limited to — the inner region of the underpart of the train (under the train and between rails), — roof equipment, namely pantographs, antennae, electrical wiring and pipes, — other roof equipment changes smaller than 20 cm in each physical dimension, — fittings, seals, bonded joints, handles and handle bars, wipers, rear view installations, surface roughness, doors, windows, glazing, signal lights, pipes, cabling and plugs, — other parts with changes in lateral dimensions smaller than 5 cm.	Documentation of differences, statement of no impact and reference to an existing compliant full conformity assessment.
Other differences in external geometry keeping the basic head shape features.	Documentation of differences and reference to an existing compliant full conformity assessment AND assessment of relative effect of differences by — moving model rig test, see 6.2.2.2, AND evidence and documentation that i) the difference does not cause changes in $U_{95\%}$ bigger than ± 10 % and ii) the new design under investigation still fulfils (on the basis of the original value from a compliant full conformity assessment and found relative difference) the requirements listed in 4.2.2.
Decrease in design speed	Documentation of differences and reference to an existing compliant full conformity assessment
Increase of design speed — less than the smaller of 20 km/h or 10 % for a train with original design speed < 300 km/h, — for a train with original design speed ≥ 300 km/h.	Documentation of differences and reference to an existing compliant full conformity assessment AND evidence and documentation based on linear extrapolation of slipstream velocity $U_{95\%}$ at new design speed that the new design under investigation still fulfils the requirements listed in 4.2.2.

4.3 Aerodynamic loads in the track bed

This point is not covered by this standard.

NOTE 1 National regulations may exist to cover this point.

NOTE 2 EN 50125-3:2003 addresses the environmental conditions for signalling and telecommunication equipment.

NOTE 3 A test method for the measurement of aerodynamic loads in the track bed in connection with the assessment of ballast projection is described in Annex A (informative).

5 Requirements on infrastructure

5.1 Train-induced pressure loads acting on flat structures parallel to the track

5.1.1 General

The train-induced pressure loads beside the track are limited by a corresponding requirement on rolling stock (see 4.1).

Flat structures parallel to the track (e.g. noise barriers) need to be designed in such a way that these train-induced aerodynamic loads can be sustained during the structure design lifetime. This requires proper provision for the dynamic character of the aerodynamic load and for the dynamic behaviour of the structure.

5.1.2 Requirements

The design of flat structures parallel to the track with GA, GB, GC gauge according to EN 15273 shall account for train-induced pressure loads as indicated in EN 1991-2. Dynamic effects need to be accounted for. To include the effect of ambient wind on the train-induced pressure loads, the wind speed component parallel to the track should be added to the train speed.

NOTE The predictive formulae stated in 6.1.3.5 of this standard are equivalent to the pressure loads graphically given in EN 1991-2, but allow a wider range of application.

5.1.3 Conformity assessment

A standard on fatigue due to dynamic loads on noise barriers from passing trains is in preparation inside CEN TC256 and will be considered for conformity assessment for noise barriers and similar structures (wind barriers, environmental screens) in a future revision of this document.

5.2 Train-induced air speeds acting on infrastructure components beside the track

This point is not covered by this standard.

NOTE National regulations may exist to cover this point.

5.3 Train-induced aerodynamic loads in the track bed

This point is not covered by this standard.

NOTE 1 National regulations may exist to cover this point.

NOTE 2 EN 50125-3:2003 addresses the environmental conditions for signalling and telecommunication equipment.

5.4 Train-induced air speed acting on people beside the track

This point is not covered by this standard.

NOTE 1 National regulations may exist to cover this point.

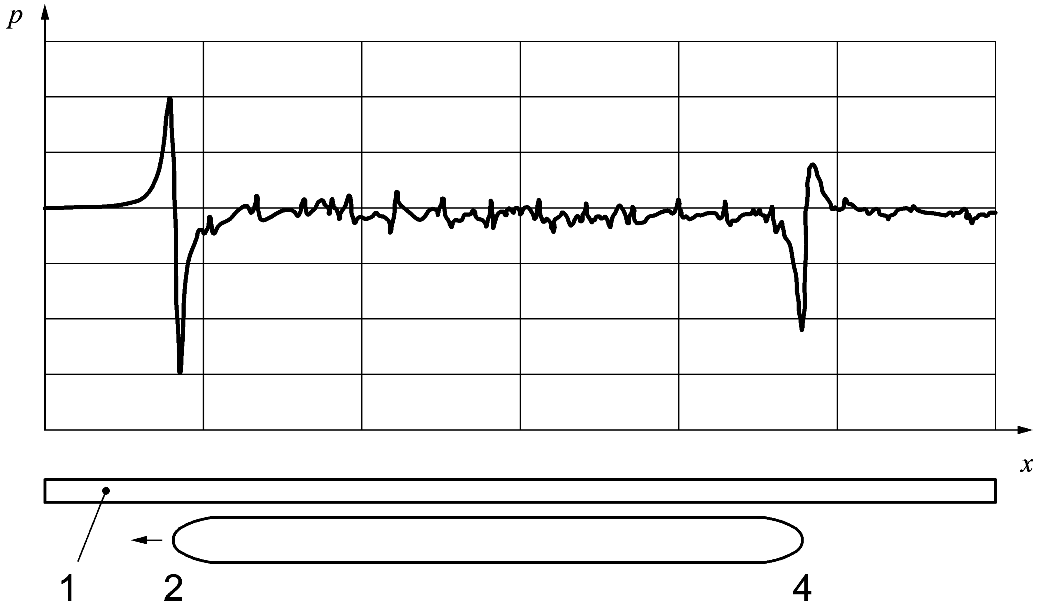
NOTE 2 Safety of passengers at platforms and workers near the track is a system issue and measures are required to control this, e.g. safe-standing clearances.

6 Methods and test procedures

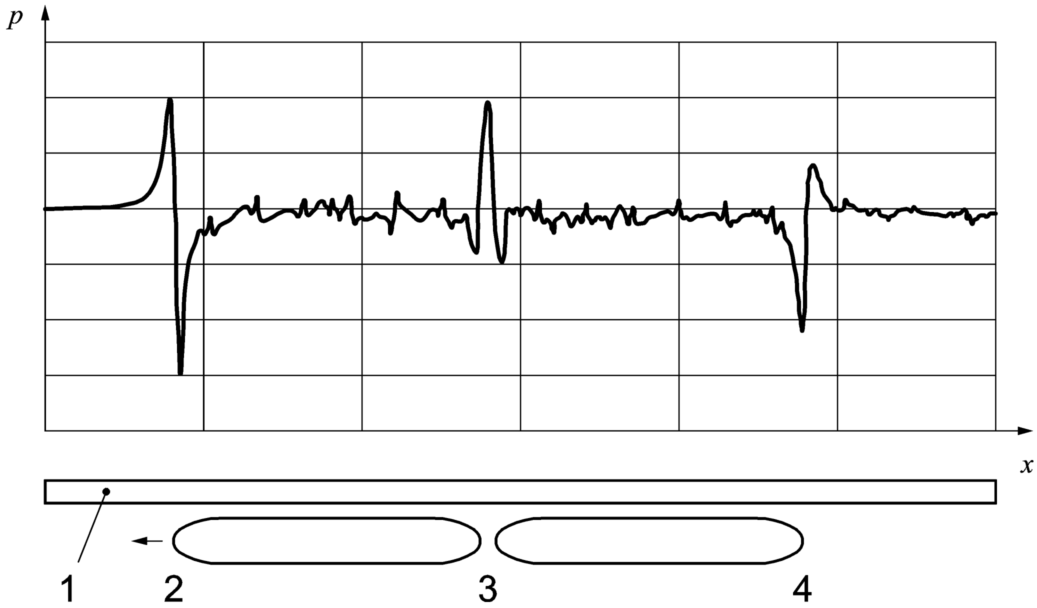
6.1 Assessment of train-induced pressure variations beside the track

6.1.1 General

A moving train causes pressure variations beside the track, which act on nearby objects. Examples for such pressure variations on a nearby vertical wall induced by the passage of a single and a double unit train are shown in Figure 2. The pressure change at a stationary point at the trackside in the absence of any object or obstacle shows qualitatively similar behaviour.



a) Single unit train



b) Double unit train

Key

1 wall

2 head of train

3 coupling of train units

4 tail of train

p pressure

x distance along wall

← running direction

Figure 2 — Examples of instantaneous pressure distributions on a vertical wall caused by the passing of a single and a double unit train

The pressure field sweeps along with the train, and therefore at a stationary point at the side of the track, the pressure p will change with time as the train passes by in a similar way to the variation with position along the length of the train.

The most severe variation of pressure is usually caused by the passage of the train head and is of the form shown in Figure 3.

Other positions where significant pressure changes may occur are at the train tail and at couplings as shown in Figure 2. However, the pressure change at the train head is considered as characteristic of all three mentioned positions (front, couplings and tail).

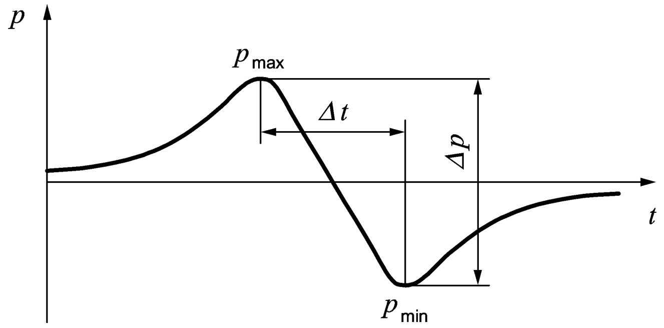


Figure 3 — Pressure variation linked to head passage of train

As the train passes, the static pressure rises to a positive peak and drops rapidly to a negative peak. The most important parameter is the peak-to-peak pressure Δp. It is related to the nose shape and is generally smaller for a longer streamlined shape than for a bluff sharp-edged shape. The time between the pressure peaks Δt can be related to the time for the length L_{n} of the train nose to pass.

$$\Delta t \approx \frac{L_{\mathrm{n}}}{v_{\mathrm{tr}}} \quad (1)$$

A smaller peak-to-peak pressure occurs as the rear of the train passes, but the order of the pressure change is reversed, such that the negative peak precedes the positive peak. Additional smaller peak-to-peak pressure occurs as the couplings of the traction train pass.

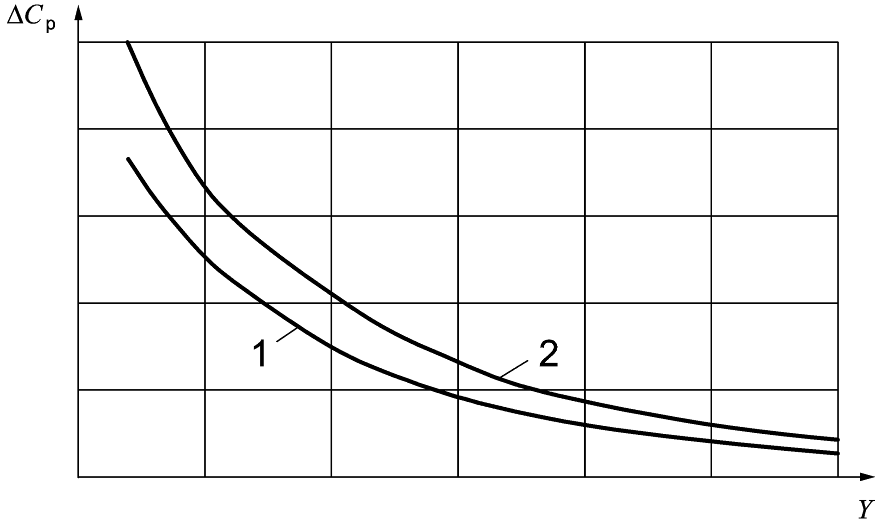
The peak-to-peak pressure is approximately proportional to the square of the speed of the train.

A non-dimensional pressure change coefficient ΔC_p is defined by:

$$\Delta C_p = \frac{2\left(p_{\mathrm{max}} - p_{\mathrm{min}}\right)}{\rho v_{\mathrm{tr}}^2} \quad (2)$$

The value of ΔC_p for the undisturbed pressure field of a particular train depends on the height above ground and the distance of the measuring point from the train, where ΔC_p decreases with increasing distance. ΔC_p is a fundamental aerodynamic property of a particular train.

An example is given in Figure 4.



Key

1 longer streamlined nose shape
2 bluff sharp-edged nose shape

Figure 4 — Typical variation of pressure change coefficient ΔC_p with lateral distance Y

Train-induced pressure variations beside the track are of special interest when they act on (i) structures parallel to the track, such as noise barriers or wind barriers, and (ii) on passing trains.

To define a clear interface between the subsystems of rolling stock and infrastructure the characteristic pressure variations beside the track are referred to the undisturbed pressure field around the train (i.e. in the absence of other objects). This also allows the train-induced pressure loads to be limited on the basis of corresponding rolling stock requirements.

Subclause 6.1.2 presents the methods for the assessment of train-induced pressure variation in the undisturbed pressure field, while subclause 6.1.3 refers to train-induced pressure loads on structures parallel to the track.

6.1.2 Pressure variations in the undisturbed pressure field (reference case)

6.1.2.1 Full-scale tests

A test site shall be chosen according to the reference case specification in 4.1.2.1. The vertical distance between the top of rail and the surrounding ground level to a distance of 3 m from the centre of the track to the side where the instrumentation is deployed and ± 10 m in x-direction from the measurement locations shall not exceed 1,00 m.

Atypical measurement positions, which provide sheltering against the train-induced pressure field, shall be excluded. Tests shall be carried out on a straight line on open track. The layout of the chosen test site shall be recorded. It shall include the description of location; topography; track cant; track profile; track interval, track formation profile and slopes.

For assessment, the rolling stock configuration shall comply with 4.1.2. Correct identification and recording of the passing train type, its speed, length and composition are mandatory (e.g. by video or by recording the passage of axles).

The meteorological conditions (air temperature, air pressure, air humidity, wind speed, wind direction) shall be measured and the state of weather recorded. Acquisition of temperature, pressure and humidity data shall comply with ISO 8756. For any rake of pressure sensors the wind speed and direction are determined by a meteorological station. It shall be installed at 2 m above top of rail, about 4 m from the track centre and as close as possible to the rake of pressure sensors, at a maximum distance of 30 m to any rake.

The reference wind speed is equivalent to the mean wind speed in the 15 s interval before the train nose passes the wind sensor. If the distance between a rake of pressure sensors and its associated meteorological station is less than 3 m, a short time wind averaging (1 s interval starting 1,2 s before the train nose passes the wind sensor) should be used to improve the correlation to the actual wind during head passage.

The tests shall consist of at least 10 independent and comparable test samples measured with reference wind speeds not exceeding 2 m/s. If available, at least 10 of those runs having the lowest wind fluctuations (i.e. the lowest standard deviation in wind speed) should be considered. The considered event of passage is at least the time period 1 s before the head passing until 1 s after the train passing. 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 $v_{\text{tr,test}}$.

The nominal test speed $v_{\text{tr,test}}$ is equal to the reference speed $v_{\text{tr,ref}}$.

Positions for pressure measurement shall be at a distance of 2,50 m from the centre of track and at heights of 1,50 m; 1,80 m; 2,10 m; 2,40 m; 2,70 m; and 3,00 m; above the top of rail. The uncertainty of sensor positioning shall be less than 0,02 m. The actual position of the sensors shall be recorded. A number of pressure rakes are permitted to be used to obtain several independent measurements from one train passage. Such rakes shall be separated from each other by a distance of at least 20 m.

The pressure sensors used shall be capable of measuring the pressure with a minimum of 150 Hz resolution. It is recommended to use sensors with a measurement range of at least 1 500 Pa.

All pressure sensors should be connected to the static pressure opening of Prandtl tubes directed in the negative x-direction, i.e. towards the train. A constant reference pressure (e.g. as stored in an insulated pressure tank) is used. In order to prevent a loss in (dynamic) information, the tubes and pipes between pressure hole and pressure sensor shall not exceed 50 cm. To prevent phase shift, all tubes shall be of equal length.

If Prandtl tubes are not used, then the alternative measurement method shall be shown to be equivalent.

The uncertainty of the pressure measurement shall be determined and may not exceed ± 2 %. The uncertainty of train speed measurement shall be determined and may not exceed ± 1 %.

The pressure signal shall be filtered with a 75 Hz 6 pole Butterworth low pass filter (or another filter with equivalent filter characteristics) and sampled at a minimum of 300 Hz. For each pressure sensor and run, the maximum peak-to-peak pressure value generated during the passage of the train head, $\overline{\Delta p}_{,\text{i}}$, shall be computed and then corrected to the reference speed and to standard air density ρ_0 = 1,225 kg/m^3 using Formula (3):

$$\Delta p_{\text{i}} = \Delta p_{\text{m,i}} \cdot \left(\frac{v_{\text{tr}}}{v_{\text{tr,i}} - v_{\text{w,x,i}}} \right)^2 \cdot \frac{\rho_0}{\rho_{\text{i}}} \qquad (3)$$

where

$v_{\text{w,x,i}}$ is the wind speed component in the x-direction.

If a correlation to cross wind is obvious, i.e. the coefficient of determination being larger than 0,5, the individual run results shall be corrected to zero cross wind speed using a linear regression of the Δp_{i} as a function of the mean cross wind speeds. A diagram showing the dependency on the cross wind and the regression line shall be reported.

The characteristic pressure difference used for further analysis is the upper bound of a 2σ interval of peak-to-peak pressure changes occurring during the passage of the train head.

$$\Delta p_{95\%} = \Delta p_{2\sigma} = \overline{\Delta p} + 2 \cdot \sigma \qquad (4)$$

where

$\overline{\Delta p}$ is the mean value over all Δp_i;

σ is the standard deviation over all Δp_i.

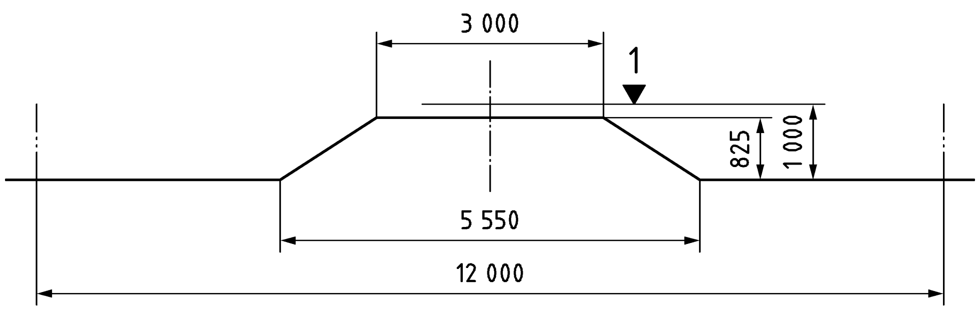
In addition to the characteristic peak-to-peak pressure difference $\Delta p_{95\%}$ during the passage of the train head, the pressure differences for the coupling passage and the tail passage should be assessed in the same manner. Further, in addition to all the characteristic peak-to-peak values, a separate analysis of the major positive and negative pressure variations should be done in a similar manner.

6.1.2.2 Reduced-scale moving model tests

The test set up shall be chosen according to the reference case specification in 4.1.2. The ground configuration should be in accordance with Figure 5.

NOTE 1 Unless otherwise stated, all dimensions are given as full-scale values.

Dimensions in millimetres



Key

1 top of rail

Figure 5 — Sketch of the track and its environment

For the determination of train head passing pressure pulse effects, it is sufficient to model the leading vehicle of the train. Models of the test train shall be constructed which accurately represent the train head. The vehicle surface shall be modelled with a tolerance of ± 10 mm full-scale maximum deviation from the original shape of the car body. The smoothness of the exterior surfaces shall be hydraulically comparable, i.e. showing relevant details, and the original vehicle design data (or real train geometry, if available) shall be provided.

Aerodynamically significant features on the train side and roof shall be modelled; it is not necessary to represent small protruding objects such as antennae, handles, etc. (diameters, gaps, obstacles smaller than 50 mm). It is less important to model the under-body of the train with precision; however, the general shape of the under-body, particularly in the regions of the snowplough and the bogies, shall be represented.

The geometry of the bogies may be simplified, with features smaller than 100 mm being ignored. However, their relative blockage effect shall be represented correctly. The pantographs may be ignored.

The Reynolds number, based on train speed, shall be larger than 250 000 to ensure that the non-dimensional $\Delta C_{p,2\sigma}$ values are representative of full scale. The non-dimensional $\Delta C_{p,2\sigma}$ values shall be demonstrated Reynolds number independent in the range 0,6 Re_{max} to Re_{max} within ± 3 %. The Reynolds number requirement implicitly specifies the model scale. The chosen scale shall be applied to the whole model configuration.

Mach number effects may be neglected provided the full-scale Mach number v_{tr} / c is lower than 0,25. When the train Mach number exceeds 0,25, the model train test speeds shall match actual train operational speeds.

The test rig parameters and ambient air conditions, i.e. temperature, pressure and humidity, shall be recorded at the time of the tests.

The tests shall consist of at least 10 independent and comparable test samples. 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 reference speed v_{tr}. The considered event of train passing shall be at least the time period starting 1 / (model scale) seconds before head passing and ending 1 / (model scale) seconds after train passing.

Data shall be sampled at a rate of at least 10 v_{tr} / (L_n · (model scale)) Hz (e.g. 2 500 Hz for a 1:25 scale model train travelling at 50 m/s and with L_n = 5 m), and then filtered at 1/4 of the sampling rate by means of a 1st order Butterworth filter or equivalent.

The pressure sensors used shall be capable of measuring the pressure with a minimum resolution of the data sampling rate. The sensors shall be calibrated prior to use over the expected pressure range. The measurement error shall be less than 2 % of the expected range. The uncertainty of the train speed measurement shall be determined and shall not exceed ± 1 %.

For each pressure sensor and moving model run, the maximum peak-to-peak pressure value generated during the passage of the train head, $\Delta p_{m,i}$, shall be computed and then corrected to the train speed of interest and to standard air density ρ_0 = 1,225 kg/m³, using Formula (5):

$$\Delta p_i = \Delta p_{m,i} \cdot \left(\frac{v_{tr,ref}}{v_{tr,i}} \right)^2 \cdot \frac{\rho_0}{\rho} \tag{5}$$

The characteristic pressure difference during the passage of the train head $\Delta p_{95\%}$ used for further analysis is the upper bound of a 2σ interval of the peak-to-peak pressure changes

$$\Delta p_{95\%} = \Delta p_{2\sigma} = \overline{\Delta p} + 2 \cdot \sigma \tag{6}$$

where

$\overline{\Delta p}$ is the mean value over all measurements Δp_i;

σ is the standard deviation over all measurements Δp_i.

Measuring positions shall be at a distance of 2,50 m from the centre of track and at heights of 1,50 m; 1,80 m; 2,10 m; 2,40 m; 2,70 m; and 3,00 m; above the top of rail. The uncertainty of sensor positioning shall be less than 0,02 m. The actual position of the sensors shall be recorded. (All heights and distances based on full scale.)

If the complete passing pressure is of interest, in addition to the characteristic peak-to-peak pressure difference $\Delta p_{95\%}$ during the passage of the train head, the pressure differences for the coupling passage and the tail passage should be assessed in the same manner. In this case the modelling requirements stated above apply to the whole model train, especially the tail. Further, in addition to all the characteristic peak-to-peak values, a separate analysis of the major positive and negative pressure variations should be done in a similar manner.

NOTE 2 Some small over-estimate of the tail passing pressure variation can result from the use of short train models due to the differences in boundary layer thickness between the short model and the long full-scale trains.

6.1.2.3 Reduced-scale static model tests

Since the train-induced pressure variation is a quasi-steady effect relative to the vehicle, conventional wind tunnel measurements can serve to assess the undisturbed pressure field at locations that are not close to the ground. Such reduced-scale tests do not serve as experimental proof of conformity, but allow economical and fast parametric studies during the concept and design phase of a train.

For these tests, the pressure is measured relative to the train and shall be transformed into a trackside coordinate system.

NOTE Unless otherwise stated, all dimensions are given as full-scale values.

The test set up should be chosen according to the reference case specification in 4.1.2. The ground configuration should be in accordance with Figure 5.

The chosen model scale shall be applied to the whole wind tunnel configuration. For the head-pressure variation measurement, it is usually sufficient to use a model of only the leading vehicle.

Models of the test train should be constructed which accurately represent the train head. The vehicle surface should be modelled with a tolerance of ± 10 mm full-scale maximum deviation from the original shape of the car body. The smoothness of the exterior surfaces should be hydraulically comparable, i.e. hydraulically smooth for most modern passenger trains. A comparison between model head region geometry, showing relevant details, and the original vehicle design data (or real train geometry, if available) should be provided.

Aerodynamically significant features on the train side and roof should be modelled; it is not necessary to represent small protruding objects such as antennae, handles, etc. (diameters, gaps, obstacles smaller than 50 mm). It is less important to model the under-body of the train with precision; however, the general shape of the under-body, particularly in the regions of the snowplough and the bogies, should be represented.

The geometry of the bogies may be simplified, with features smaller than 100 mm being ignored. However, their relative blockage effect shall be represented correctly. The pantographs may be ignored.

The Reynolds number, based on the wind tunnel air speed, shall be larger than 250 000 to ensure that the ΔC_p values are representative of full scale. The ΔC_p values should be demonstrated to be Reynolds number independent in the range 0,6 Re_{max} to Re_{max}, with the variation in values being no more than ± 3 %.

Mach number effects can be neglected provided the full-scale Mach number is lower than 0,25.

The wind tunnel parameters and ambient air conditions shall be recorded.

Since the pressure variation is a quasi-steady phenomenon (in this situation) in the train-based coordinate system, conventional pressure transducers and manometers are suitable and the length of the connecting tubes is of no importance. The pressure shall be measured with an appropriate static pressure probe at the desired locations. The effect of the wind tunnel type, e.g. blockage effects, should be considered. The accuracy of the pressure sensors shall be ± 1 % of the peak-to-peak pressure reading.

The longitudinal extent of the measurements should start about one vehicle length in front of the leading vehicle and should extend to about one vehicle length after the train head, e.g. the static pressure probe shall be traversed along the train. Each pressure reading shall be time-averaged until the mean value is stable to within ± 1 %.

The spatial variation dx of the head pressure shall be transformed into the temporal variation $d\,t$ analogous to full-scale measurements using $d\,t = d\,x\,/\,v_{\text{tr}}$. The magnitude of the head pressure variation coefficient ΔC_p shall not be transformed.

Measuring positions should be at a distance of 2,50 m from the centre of track and at heights of 1,50 m; 1,80 m; 2,10 m; 2,40 m; 2,70 m; and 3,00 m; above the top of rail. The uncertainty of sensor positioning shall be less than 0,02 m. The actual position of the sensors shall be recorded.

It is recommended that tests should be repeated for yaw angles of ± 5° to give an estimate of the influence of cross wind in full-scale measurements.

6.1.2.4 Numerical simulations

6.1.2.4.1 General

Three dimensional CFD flow simulation tools that account for friction, separation and vorticity shall be used.

The three-dimensional, high Reynolds number turbulent flow around a vehicle is usually characterized by the following: decelerations and accelerations, curved boundaries, separation, possible reattachment, recirculation and swirling properties. In general, sufficiently accurate solutions may be achieved by turbulence modelling through approaches such as:

— Reynolds Averaged Navier-Stokes (RANS); or

— codes based on the Lattice Boltzmann Method. (These methods require the volume containing the flow of interest to be discretized into sub-volumes or cells in which approximations to the physical formulae are solved);

— generally by a validated implementation of a widely accepted turbulence model.

All the above-mentioned approaches are known by the generic name of computational fluid dynamic methods (CFD). The chief challenge of CFD is the appropriate choice of an adequate combination of computational domain sub-division (mesh cells or grid points), boundary conditions, computational method and turbulence modelling.

Those undertaking CFD simulations and analysis of the results should be able to demonstrate competency through a proven record of vehicle aerodynamic calculations. The operator also shall show that he is able to meet the benchmark case requirements.

The set up shall be chosen according to the reference case specification in 4.1.2. The ground configuration should be in accordance with Figure 5. The rails may be modelled.

The classification of a vehicle shape as streamlined shall be based on examination of the flow simulation results.

6.1.2.4.2 Benchmark tests

In order to demonstrate the appropriateness of the CFD approach, calculations shall be made for at least one benchmark vehicle with a similar streamlined or bluff geometry. The calculated pressure shall be compared to the pressures from the reference vehicle obtained from full-scale tests according to 6.1.2.1 or from reduced-scale tests according to 6.1.2.2.

It shall be demonstrated that ε, the relative r.m.s. (root mean square) of the difference between the calculated pressure variation and the test results over all heights (see Formula 7) lies within - 5 % and + 10 % for a bluff vehicle or within - 3 % and + 5 %, in case of a streamlined vehicle.

$$\varepsilon = sign\{\sum_i [(sign(\Delta p_{\text{CFD,i}} - \Delta p_{\text{test,i}})(\Delta p_{\text{CFD,i}} - \Delta p_{\text{test,i}})^2]\}\sqrt{\frac{\sum_{i=1}^{6}(\Delta p_{\text{CFD,i}} - \Delta p_{\text{test,i}})^2}{\sum_{i=1}^{6}\Delta p_{\text{test,i}}^2}} \tag{7}$$

The same set-up related to the simulation domain, the local mesh size in different domain regions, the turbulence model and the boundary conditions is then considered to be appropriate for calculating head pressure variations. This set-up shall be used for the vehicle to be investigated.

The benchmark calculations should be repeated when changes are made to the CFD software, (including upgrade releases of the same software package), or to the operational personnel who ran the benchmark calculations.

6.1.2.4.3 Vehicle model

It is generally sufficient to model only the leading vehicle. However, it may be advantageous to either extrude the cross-section of the leading vehicle or to add additional coaches such that the vehicle model extends up to the downstream end of the computational domain.

The vehicle surface shall be modelled with a tolerance of ± 10 mm full-scale maximum deviation from the original shape of the car body. The smoothness of the exterior surfaces shall be hydraulically comparable, i.e. hydraulically smooth for most modern passenger trains. Where there are localized regions of increased surface roughness, these shall be modelled in a proper way. Curved surfaces shall be modelled with sufficient grid resolution as to avoid artificial flow separations due to polygonal approximations.

A comparison between the discretized surface of the rolling stock head region, showing relevant details, and the original vehicle design data (or real train geometry, if available) shall be provided.

Aerodynamically significant features on the train side and roof shall be modelled; it is not necessary to represent small protruding objects such as antennae, handles, etc. (diameters, gaps, obstacles smaller than 50 mm). It is less important to model the under-body of the train with precision; however, the general shape of the under-body, particularly in the regions of the snowplough and the bogies, shall be represented. Contact between the wheels and rail or ground may be simplified to avoid skewed volume elements near the contact point.

The geometry of the bogies may be simplified, with features smaller than 100 mm being ignored. However, their relative blockage effect shall be represented correctly. The pantographs may be ignored.

It is possible to take advantage of the symmetry of the model and therefore mesh only one half of the computational domain if the full scale vehicle has only slight asymmetries, e.g. in the underfloor region or on the roof in case of a steady Reynolds Averaged Navier-Stokes (RANS) simulation, only. The use of a symmetric model shall be justified.

6.1.2.4.4 Computational domain

The domain boundaries shall not interfere with the flow around the vehicle in a physically incorrect way. The domain consists of a large air volume above the ground with a representation of the ballast and rails. The domain extensions shall be at least 50 m in each direction from the rolling stock nose position. The blockage ratio shall be smaller than 0,01.

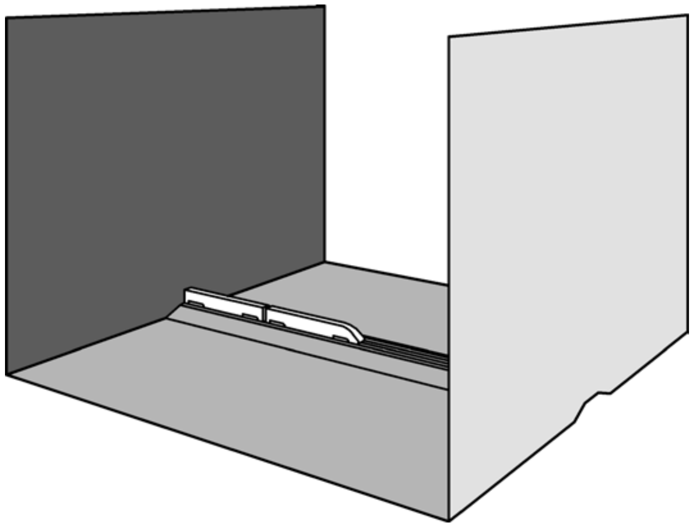


Figure 6 — Simulation domain with train model

A ballast bed as specified in Figure 5 should be extruded through the domain as illustrated in Figure 6.

6.1.2.4.5 Computational domain sub-division

The type of CFD method chosen dictates whether a volume discretization or surface discretization is used.

The volume discretization shall represent, with sufficient resolution, the flow regions where high pressure and velocity gradients are expected such as: boundary layers, shear layers, large vortical structures, stagnation zones, recirculation zones, separation bubbles, wakes, etc. Particular regions of interest are e.g. the front end, the coupling device and the snowplough.

The volume discretization shall meet basic requirements concerning wall units adjacent to no-slip walls, appropriate for the selected computational method and turbulence model. For RANS simulations, typical values for the dimensionless wall distance y^+ to be used for the first cell layer should be of the order of 1 for low Reynolds number near-wall treatment, and typically 30 to 150 for high Reynolds number turbulence models using wall functions.

The surface discretization shall take into account the relevant pressure gradients and the surface geometry.

The aerodynamic pressure shall be demonstrated to be sufficiently independent of the volume or surface discretization used through appropriate sensitivity analyses (e.g. grid convergence study).

6.1.2.4.6 Turbulence modelling

Turbulence models are based on engineering assumptions to predict turbulent stresses. These stresses emerge as a result of averaging or filtering of the non-linear convection terms of the governing flow formulae. They may be regarded as an extra viscosity that for turbulent flows are sometimes several orders of magnitude larger than the molecular viscosity. However, no universal turbulence model exists.

The chosen turbulence model shall resolve the following relevant physical phenomena where present:

— non equilibrium flow – e.g. two equation models;

— realizable turbulent stress – i.e. non-constant anisotropic coefficient required;

— realizable time scale modelling – prevent unphysical maxima caused by insufficient spatial resolution;

— 3D flow structures with secondary flow effects – implicit or explicit Reynolds stress modelling.

For other models or methods used in conjunction with LES (Large Eddy Simulation) or DES (Detached Eddy Simulation) it shall be shown that the physical modelling assumptions are valid for the chosen set-up.

6.1.2.4.7 Boundary conditions

All tests shall be performed at 15 °C ambient temperature with an ambient pressure of 101 325 Pa and at standard air density ρ_0 = 1,225 kg/m^3 and dynamic viscosity η = 1,78·10^{-5} Pa·s. No wind, such as a headwind, a tailwind or a crosswind, shall be applied.

The onset wind profile relative to the train shall be uniform, i.e. a block profile.

The outlet boundary condition shall be appropriate for the train configuration under consideration, e.g. a constant pressure or conservation of mass boundary condition. The surfaces of the train shall be treated as no-slip walls. The ground and track bed shall be treated as no-slip walls moving with the same velocity of the onset wind profile. The top and lateral plane boundary conditions shall be appropriate to represent far-field conditions.

6.1.2.4.8 Numerical method

The applied method shall be at least second order accurate for all spatial and temporal discretized terms.

6.1.2.4.9 Assessment of calculated head pressure variation

The pressure variations alongside the rolling stock shall be simulated at heights of 0,50 m; 1,50 m; 1,80 m; 2,10 m; 2,40 m; 2,70 m; 3,00 m and 3,30 m above the top of rail at a distance of 2,50 m from the track centre.

The head pressure variation generated by the vehicle shall be quantified in the following way:

For both steady and unsteady simulations, the requirement is the assessment of the maximum peak-to-peak pressure variation $\Delta p_{95\%}$ at heights of 1,50 m; 1,80 m; 2,10 m; 2,40 m; 2,70 m and 3,00 m above the top of rail at a distance of 2,50 m from the track centre (based on full scale).

The $\Delta p_{95\%}$ is obtained as shown in Table 8

Table 8 — Calculation of $\Delta p_{95\%}$ from CFD simulation

	Steady	Unsteady
streamline shaped vehicles	$\Delta p_{95\%} = 1{,}03 \cdot \overline{\Delta p_{\text{sim}}}$	$\Delta p_{95\%} = 1{,}03 \cdot \Delta p_{\text{sim}}$
bluff shaped vehicles	$\Delta p_{95\%} = 1{,}05 \cdot \overline{\Delta p_{\text{sim}}}$	$\Delta p_{95\%} = 1{,}03 \cdot \Delta p_{\text{sim}}$

where

$\overline{\Delta p_{\text{sim}}}$ is the head pressure variation obtained by steady calculations;

Δp_{sim} is the head pressure variation obtained by unsteady calculations as explained hereafter.

For unsteady calculations, all the time steps after reaching a stable mean flow field (i.e. more than the time of ten passages of the head length including the first bogie) shall be post-processed as follows:

— the CFD solution is calculated in a reference frame moving with train speed. Hence, the transient pressure information extracted during calculation is collected along lines corresponding to the measurement positions, i.e. 15 m ahead of the train head to -15 m past the train head, y = 2,5 m, z = positions 1,50 m; 1,80 m; 2,10 m; 2,40 m; 2,70 m and 3,00 m. For better accuracy the line extracts for each time step shall be taken at the corresponding grid positions (using the CFD discretization and not spatial interpolation);

— to mimic the passage of fixed pressure probes, the transient information is interpolated on the traces expressed by the motion function x = 15 m + $(i - 1) \cdot 25$ m – $(t - t_0) \cdot v_{\text{tr}}$, where i is the number of the individual run (i = 1 to 10). For each time step of the computation one pressure value (per probe) shall be determined. The resulting time histories shall not be filtered;

— calculate the $\overline{\Delta p_{\text{sim}}}$ and the standard deviation (σ_{sim}) of all the peak-to-peak pressure signals (time histories) at each height to determine Δp_{sim} as follows:

$$\Delta p_{\text{sim}} = \overline{\Delta p_{\text{sim}}} + 2 \cdot \sigma_{\text{sim}} \tag{8}$$

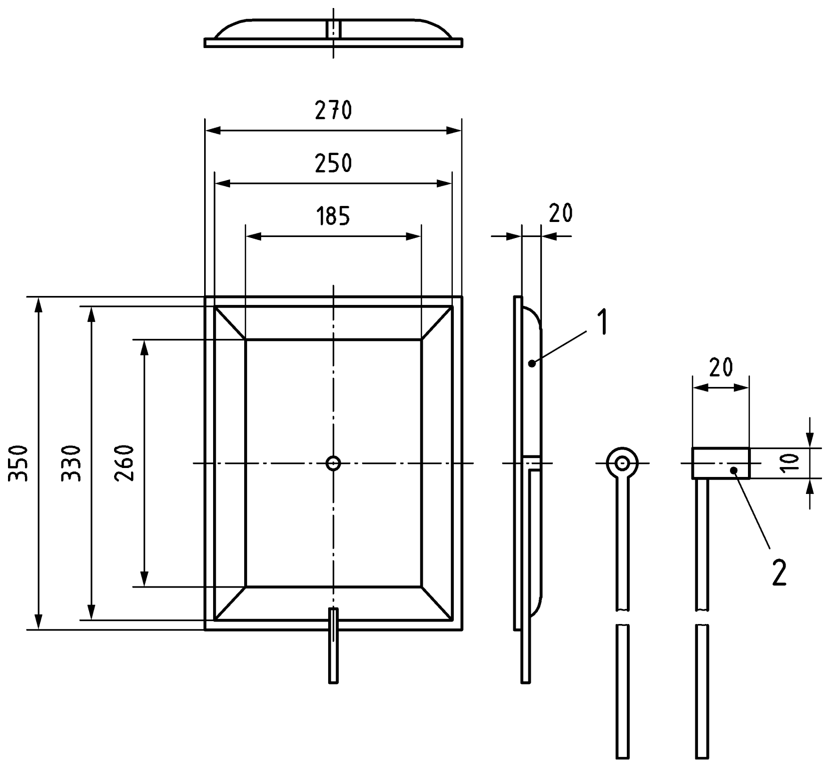
6.1.3 Pressure variations on surfaces parallel to the track

6.1.3.1 Full-scale tests

Tests shall be carried out following the same requirements as stated in 6.1.2.1, apart from the pressure measurement itself.

Pressure measurements should be undertaken using pressure tappings through the surface if practicable and if the surface is smooth. If this is not possible, then a flat mounting board should be used with the tappings set in it. The mounting board shall be set on the surface and should be as thin as possible. An example is shown in Figure 7.

Dimensions in millimetres



Key

1 smooth plate

2 pressure tapping

Figure 7 — Example of schematic description of set up for pressure measurement

The pressure difference between two surfaces may be measured as differential pressures relative to a common reference pressure (e.g. as stored in an insulated pressure tank).

The spacing of the pressure tappings should be fine enough to resolve the pressure field. If the actual pressure loading on vertical structures is to be assessed, it is recommended to locate pressure transducers at heights of 0,50 m; 1,50 m; 2,50 m; 3,50 m from top of rail.

6.1.3.2 Reduced-scale moving model tests

Tests shall be carried out following the same requirements as stated in 6.1.2.2, apart from the pressure measurement on the surface parallel to the track. The model scale of the structure shall be the same as that of the train.

The spacing of the pressure tappings should be fine enough to resolve the pressure field. If the actual pressure loading on vertical structures is to be assessed, it is recommended to locate pressure transducers at full-scale heights of 0,50 m; 1,50 m; 2,50 m and 3,50 m from top of rail.

6.1.3.3 Reduced-scale static model tests

Reduced-scale static model tests to investigate pressure variations on surfaces parallel to the track shall follow the same requirements as stated in 6.1.2.3 but are subject to more restrictions.

Such tests are only appropriate where the structures are very long and not located or investigated in the direct vicinity of the ground (e.g. platform roofs or noise barriers). The model scale of the structure shall be the same as that of the train. The model of the structure should be rounded at the front and have a full-scale length of 20 m ahead of the nose of the vehicle model, and at least 10 m downstream of the nose.

The spacing of the pressure tappings should be fine enough to resolve the pressure field. If the actual pressure loading on vertical structures is to be assessed, it is recommended to locate pressure transducers at full-scale heights of 0,50 m; 1,50 m; 2,50 m and 3,50 m from top of rail.

6.1.3.4 Numerical simulation

Numerical simulations to investigate pressure variations on surfaces parallel to the track shall follow in principle the same requirements as stated in 6.1.2.4. If the actual pressure loading on vertical structures is to be assessed, it is recommended to calculate the pressure changes at full-scale heights of 0,50 m; 1,50 m; 2,50 m and 3,50 m from top of rail.

6.1.3.5 Predictive formulae

6.1.3.5.1 General

The following subclauses apply to railway operation on gauges GA, GB and GC according to EN 15273. They allow a determination of characteristic pressure values which are in line with those given graphically in EN 1991-2 but allow a wider range of application by use of formulae.

NOTE According to the ERRI report D189 Rp1 the given characteristic pressure values are usually based on the maximum area-averaged (dynamic) loads on a structure.

Since a train passing does not result in a static load, these characteristic values cannot be taken as maximum static loads. Fatigue calculations require additional information on the dynamic behaviour of the structure, the number of cycles, more detailed information on the dynamics of the train-induced pressure variation, etc. A standard on fatigue due to dynamic loads on noise barriers from passing trains is in preparation inside CEN TC256 and will be considered in a future revision of this document.

6.1.3.5.2 Flat vertical structures parallel to the tracks

The following structures belong to this category:

- noise barriers;
- wind barriers;

— façades of buildings close to tracks.

If results from measurements, calculations or simulations are not available, the pressure signal (which corresponds to the head and the tail of the train passing the structure) is replaced by the distributed loads $+p_{1k}$ and $-p_{1k}$, each of which is 5 m in length, and moving at the speed of the train, as shown in Figure 8.

The load shall apply from the foot of the structure on the railway track formation up to a maximum of 5 m above the top of the rail (see Figure 8).

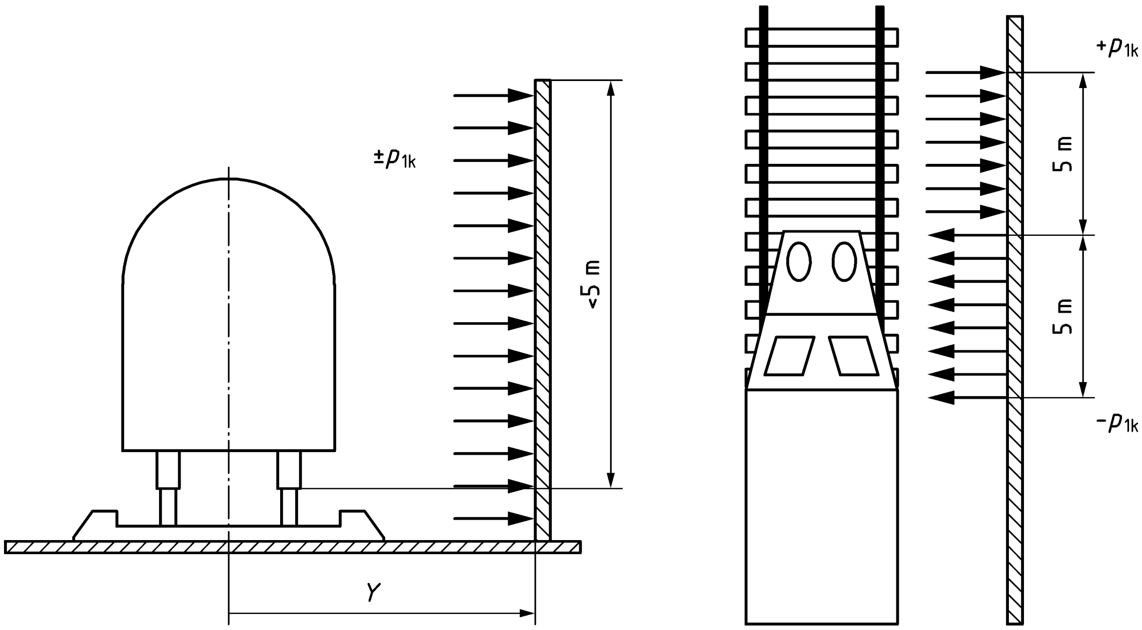


Figure 8 — Load on flat vertical structures parallel to the tracks

The characteristic values p_{1k} of the distributed loads are determined from Formula (9).

$$p_{1k} = \frac{\rho v_{tr}^2}{2} k_1 C_{p1} \tag{9}$$

where

C_{p1} is the aerodynamic coefficient depending on the distance from track centre Y;

k_1 is a shape coefficient of the train.

The factor C_{p1} is obtained from Formula (10).

$$C_{p1} = \frac{2,5}{(Y + 0,25)^2} + 0,02 \tag{10}$$

for $Y \geq 2,30$ m.

The k_1 values are as follows:

k_1 = 1,00 for freight trains;

k_1 = 0,85 for passenger trains;

k_1 = 0,60 for high-speed trains with a train speed equal to or greater than 250 km/h that are very well shaped aerodynamically.

In the case of small structural elements up to 1,00 m high or up to 2,50 m long, the pressures p_{1k} shall be increased by a factor of 1,3.

6.1.3.5.3 Flat horizontal structures above the tracks

The following flat horizontal structures above the tracks belong to this category:

- catenary protective structures;
- bridge decks and gangways.

If results from measurements, calculations or simulations are not available, the pressure signal is replaced by the distributed loads $+p_{2k}$ and $-p_{2k}$, each 5 m long, up to 20 m wide, centred on the track centre, and moving at the speed of the train as shown in Figure 9.

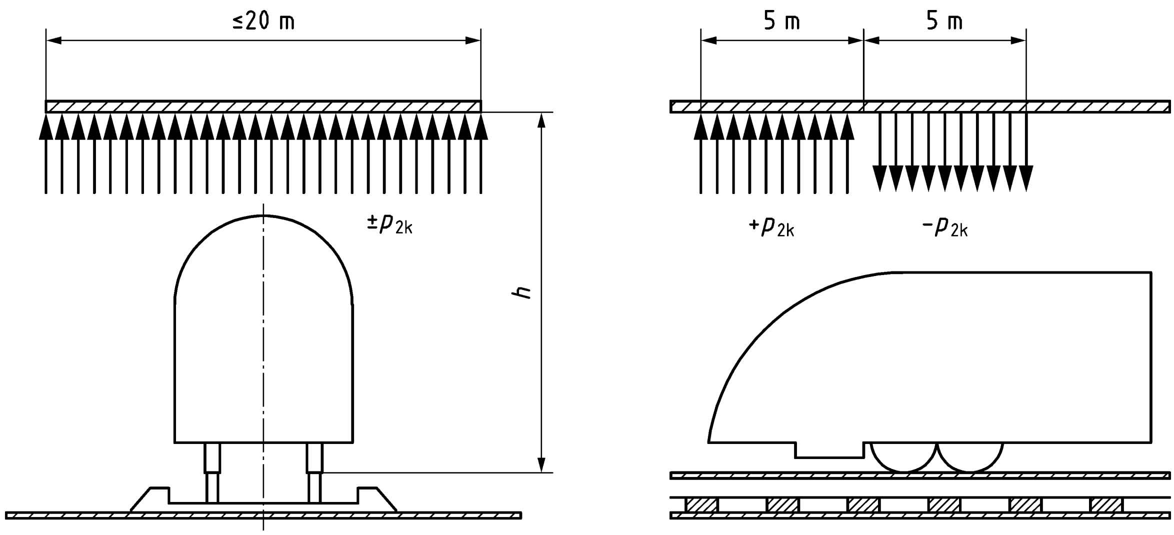


Figure 9 — Load on flat horizontal structures above the tracks

The values p_{2k} of the distributed loads are determined from Formula (11).

$$p_{2k} = \frac{\rho v_{tr}^2}{2} k_2 C_{p2} \tag{11}$$

Here, k_2 takes the same values as k_1 given in 6.1.3.5.2.

The coefficient C_{p2} is obtained from Formula (12).

$$C_{p2} = \frac{2}{(h-3{,}10)^2} + 0{,}015 \tag{12}$$

where

h is the height above top of rail in metres to the lower face of the structure considered.

Pressures $\pm p_{2k}$ should be applied over the width of the surface studied up to 10 m on either side of the track centre.

NOTE This is a conservative assumption for the load.

In the case of passing trains, the pressures are superimposed. However, there is no need to consider more than two tracks.

6.1.3.5.4 Flat horizontal structures close to tracks

The following flat horizontal structures close to tracks belong to this category:

— platform canopies with a minimum height of 3,80 m above rail comprising a roof, resting on posts, without either a backwall on the platform parallel to the passing train or without the blockage caused by a stationary train located on track adjacent to the platform edge furthest away from the passing train.

If results from measurements, calculations or simulations are not available for this type of structure, the pressure signal caused by the head and tail passing is approximated by the distributed loads $\pm p_{3\mathrm{k}}$, each 5 m long and moving at the speed of the train (see Figure 10).

Values of $p_{3\mathrm{k}}$ reduce with increasing horizontal distance Y from the track centre.

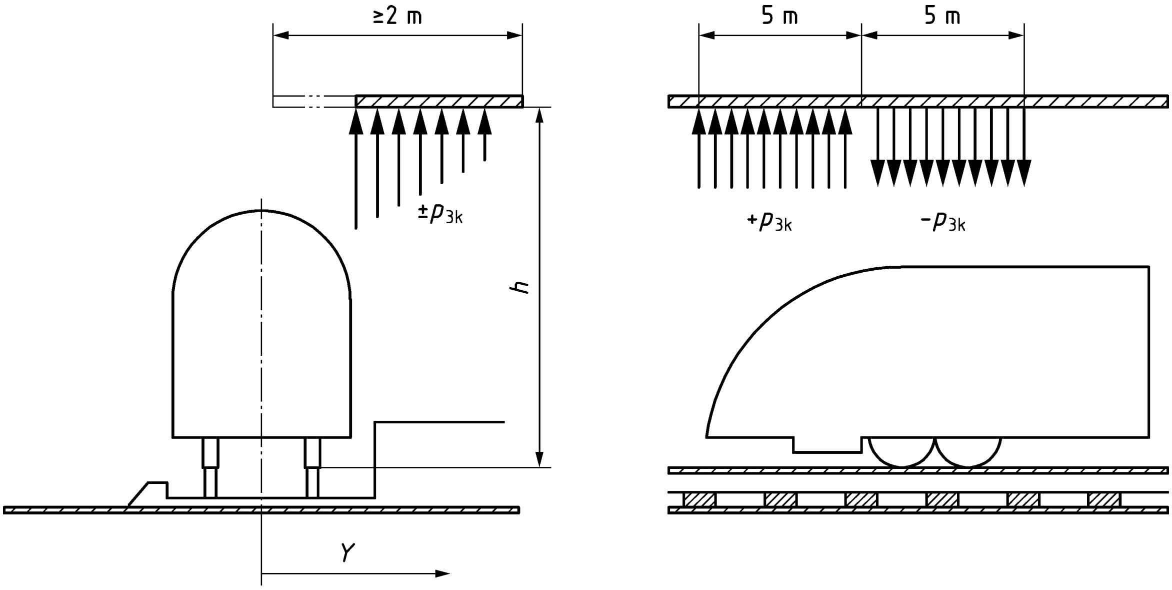


Figure 10 — Load on flat horizontal structures close to the tracks

Values $p_{3\mathrm{k}}$ of the loads which depend on Y are determined from Formula (13).

$$p_{3\mathrm{k}} = \frac{\rho v_{\mathrm{tr}}^2}{2} k_3 C_{p3} \tag{13}$$

The coefficient C_{p3} is given by Formula (14).

$$C_{p3} = \frac{1,5}{(Y + 0,25)^2} + 0,015 \tag{14}$$

$p_{3\mathrm{k}}$ should be calculated for the structure being considered as a function of the distance Y, to the axis of the nearest track.

The pressures are cumulative for a structure flanked by two tracks.

Factor k_3 is dependent upon h as follows:

$k_3 = \frac{7{,}50 - h}{3{,}70}$ for 3,80 m $\leq h < 7{,}50$ m

$k_3 = 0$ for $h \geq 7{,}50$ m

where

h is the distance between the top of the rail and the lower face of the structure being considered.

6.1.3.5.5 Mixed vertical and horizontal or inclined structures close to the tracks

The following structures belong to this category:

- screens with a vertical part plus an inclined or horizontal part, called mixed screens;
- platform canopies comprising a roof and a backwall, which serves as a support or a space-filler space between the supports;
- platform canopies comprising a roof covering a waiting room or any other enclosed building;
- platform canopies on posts situated between two tracks, where trains can be standing on the adjacent track.

If results from measurements, calculations or simulations are not available for this type of structure, the pressure signal caused by the passage of the head and tail of the train is approximated by the distributed loads of type $\pm p_{1k}$. These are each 5 m long and moving at the speed of the train, applied perpendicular to the surfaces considered (see Figure 11).

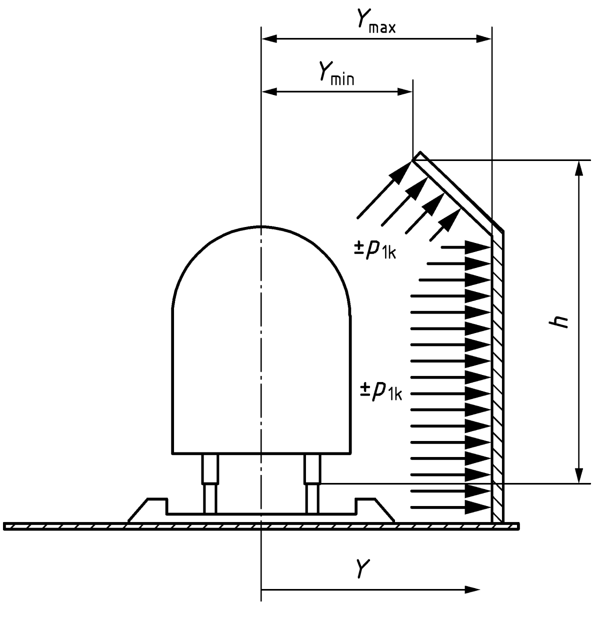


Figure 11 — Load on mixed vertical and horizontal or inclined structures close to the tracks

The equivalent loads are greater in this case than in the case of purely vertical or horizontal surfaces. These values shall be determined from Formula (9) in 6.1.3.5.2 except that the following distance should be used in Formula (10):

$$Y = 0{,}6 Y_{min} + 0{,}4 Y_{max} \quad (15)$$

where

Y_{min} is the minimum horizontal distance of the surface from the track centre;

Y_{max} is the maximum horizontal distance of the surface from the track centre.

If $Y_{max} > 6$ m, then $Y_{max} = 6$ m is assumed.

6.1.3.5.6 Closed structures enveloping the tracks over a limited length up to 20 m

The following structures belong to this category:

— structures containing a horizontal surface above the tracks and at least one vertical surface;

— concrete moulds (e.g. used during bridge deck construction);

— provisional structures (e.g. service walkways);

— catenary protective structures on overhead bridge abutments close to the tracks (e.g. portal structure, frames, etc.).

If results from measurements, calculations or simulations are not available for this type of structure, the pressure signal caused by the passage of the head and tail of the train may be approximated by $\pm p_{1k}$ and $\pm p_{2k}$.

The loads $\pm p_{1k}$ and $\pm p_{2k}$ are approximated as described in the formulae given in 6.1.3.5.2 and 6.1.3.5.3 and shall be multiplied by the following factors:

— 2 for loads p_{1k} on a vertical surface (see Figure 12);

— 2,5 for loads p_{2k} on a horizontal surface, if the structures enclose one track;

— 3,5 for horizontal loads p_{2k} on a horizontal surface, if the structures enclose two tracks (see Figure 12).

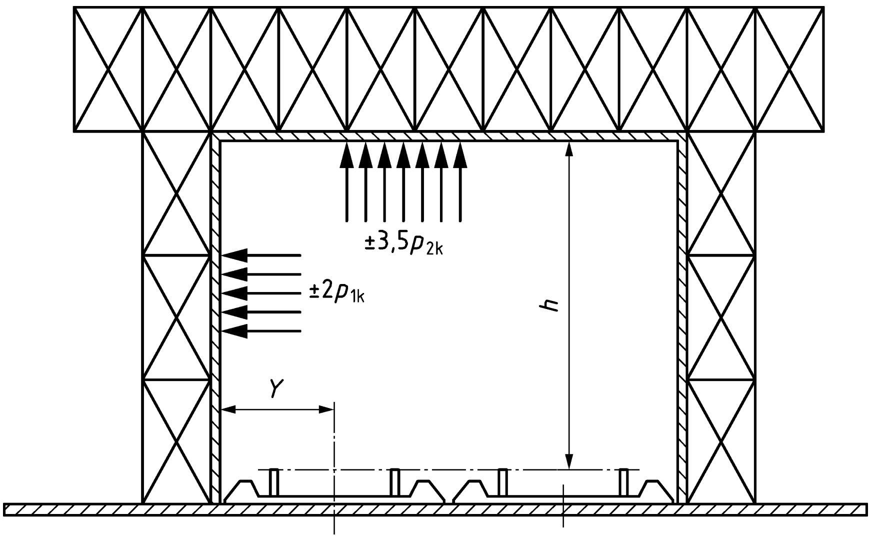


Figure 12 — Loads for vertical and horizontal surfaces of structures enclosing two tracks

6.1.4 Effect of wind on loads caused by the train

If the effect of ambient wind shall be included in the estimate of the head pressure variation during train passage, the wind speed component parallel to the track should be added to the train speed.

6.2 Assessment of train-induced air flow beside the track

6.2.1 General

The train-induced loading on persons by the track is dominated by slipstream effects. Thus, it is characterized by an assessment of air speed. As well as the train, the geometry of the track and its surroundings also have strong effects on train-induced slipstream velocities.

Train-induced airflows beside the track also cause aerodynamic forces on objects. For small objects, the aerodynamic forces are often assessed using the air speed within the undisturbed flow field.

The speed and the direction of train-induced airflow change rapidly during the passing of a train.

In addition to the aerodynamic loading caused by train-induced airflows, the aerodynamic loading caused by ambient wind shall be taken into account.

6.2.2 Slipstream effects on persons beside the track (reference case)

6.2.2.1 Full-scale tests

A test site shall be chosen according to the reference case specification in 4.2.2. The vertical distance between the top of rail and the surrounding ground level to a distance of 3 m from the centre of the track to the side where the instrumentation is deployed and ± 10 m in x-direction from the measurement locations shall not exceed 1,00 m.

Atypical measurement positions, which provide sheltering against the train-induced airflows shall be excluded. Tests shall be carried out at a straight line on open track. The layout of the chosen test site shall be recorded. It shall include the description of location; topography; track cant; track profile; track interval and slopes.

For assessment, the rolling stock configuration shall comply with 4.2.2. Correct identification and recording of the passing train type, its speed, length and composition are mandatory (e.g. by video or by recording the passage of axles).

The meteorological conditions, (air temperature, air pressure, air humidity, wind speed, wind direction) shall be measured and the state of weather recorded. Acquisition of temperature, pressure and humidity data shall comply with ISO 8756. For any rake of anemometers the ambient wind speed and direction are determined by the test anemometer at 1,4 m above the track.

The reference wind speed for the test sample is equivalent to the mean wind speed in the 3 s interval between 4 s and 1 s before the first axle of the train passes the anemometer.

The tests shall consist of at least 20 independent and comparable test samples measured with reference wind speeds not exceeding 2 m/s. The slipstream airflow measurement shall start at least 4 s before the train nose passes and continue until at least 10 s after the train tail has passed. For a valid set of measurements, at least 50 % of the measurements shall be taken within ± 5 % of the nominal test speed and all of the measurements shall be within ± 10 % of the nominal test speed $v_{\text{tr,test}}$.

The nominal test speed is

$v_{\text{tr,test}} = v_{\text{tr,ref}}$ or

$v_{\text{tr,test}}$ = 250 km/h or $v_{\text{tr,max}}$, whichever is lower

Positions for slip-stream measurement shall be at a distance of 3,00 m from the centre of track and at heights of 0,20 m and 1,40 m above the top of rail. The uncertainty of sensor positioning shall be less than 0,02 m. The actual position of the sensors shall be recorded. If several anemometers are used to reduce the number of test runs required, there shall be a distance of at least 20 m between the anemometers to ensure independent samples and to avoid interference effects.

The sensors used shall be capable of measuring the airflow in the x- and y-directions and shall be capable of correctly resolving 3 Hz oscillations in the flow. The signal shall be sampled at a minimum of 10 Hz. It is recommended to use sensors with a measurement range of at least ± 30 m/s.

The uncertainty in the air speed measurements shall be determined and shall not exceed ± 3 % for wind speeds above 6 m/s or ± 0,2 m/s for wind speeds of less than 6 m/s. The uncertainty of train speed measurement shall be determined and may not exceed ± 1 %.

For each probe and run i the time signal of the resultant horizontal air speed during the whole passage is then computed and transformed to the reference train speed.

$$u_{\mathrm{i}}(t_{\mathrm{i}}) = u_{\mathrm{m,i}}(t_{\mathrm{m,i}}) \cdot \frac{v_{\mathrm{tr,ref}}}{v_{\mathrm{tr,i}}} \tag{16}$$

where

$t_{\mathrm{i}} = t_{\mathrm{m,i}} \dfrac{v_{\mathrm{tr,i}}}{v_{\mathrm{tr,ref}}}$;

$v_{\mathrm{tr,i}}$ is the train speed for test i;

$v_{\mathrm{tr,ref}}$ is the reference speed as defined in 4.2.2.

Data analysis shall then include a low pass filtering of the air speed data u_{i} (t_{i}) with a 1 s moving average, or equivalent, (equivalency shall be demonstrated), to determine the maximum horizontal air speed U_{i}.

NOTE This means that the value of U_{i} at a height of 1,4 m is evaluated by scaling the measurement made at a nominal speed of $v_{\mathrm{tr,ref}}$ to a speed of 200 km/h when $v_{\mathrm{tr,ref}}$ exceeds 200 km/h.

The characteristic air speed used for further analysis is the upper bound of a 2σ interval of the maximum resultant horizontal air speed during the whole passage

$$U_{95\%} = U_{2\sigma} = \overline{U} + 2 \cdot \sigma \tag{17}$$

where

$\overline{U}$ is the mean value over all U_{i};

σ is the standard deviation of all U_{i}.

6.2.2.2 Reduced-scale tests

Moving model tests are an appropriate method for assessing train-induced airflows, as they can account for unsteady effects. Such reduced-scale tests do not serve as experimental proof of conformity to specifications or homologation requirements. Their main purpose is to assess airflow characteristics during the concept and design phase of a train and to support parametric studies.

Models of the test train shall be constructed which accurately represent the train head and tail and have a good but not necessarily highly detailed representation of the bogies, inter-car gaps and train exterior surfaces. The chosen scale shall be applied to the whole model configuration (train, potential structures and/or objects and their distance to the train, measuring positions). The basic shape of the train body shall be modelled in width and height to a tolerance of ± 0,02 m full scale from the true shape. The smoothness of the exterior surfaces shall by hydraulically comparable, i.e. hydraulically smooth for most modern passenger trains.

The Reynolds number shall be larger than 250 000 to ensure that values for $U_{2\sigma} / v_{tr}$ are representative of full scale. The values for $U_{2\sigma} / v_{tr}$ shall be demonstrated Reynolds number independent in the range 0,6 Re_{max} to Re_{max} within ± 3 %. The Reynolds number requirement implicitly specifies the model scale.

Mach number effects may be neglected provided the full-scale Mach number is lower than 0,25.

The test rig parameters and ambient air conditions, i.e. temperature, pressure and humidity, shall be recorded at the time of the tests.

Some variability of speeds between test runs is allowable during testing (± 3 %). The considered event of train passing is at least the time period starting 1 s before head passing and ending 10 s after train passing (full scale).

Data shall be sampled at a rate of at least 10 / (model scale) Hz (e.g. 250 Hz at 1:25 model scale), and then filtered at 1/10 the sampling rate by means of a 1st order Butterworth filter or equivalent. This corresponds to capturing full-scale data at 10 Hz and filtering at 1 Hz.

The x and y components of wind speed shall be measured at the trackside using anemometers with a suitable temporal resolution. Commonly utilized anemometers are hot-wire anemometers and Laser-Doppler anemometers, but other instruments may be used if appropriate. The slipstream speed shall be obtained by forming the vector sum of the x-y speed components. The measurement error shall be less than 1 % of the expected range.

The anemometers shall have a valid calibration. If hot wires are utilized, they shall be calibrated before use and when ambient temperature changes affect the hot wire calibration curves.

The tests shall consist of at least 20 independent and comparable test samples.

For each moving model run, the maximum resultant horizontal air speed during the whole passage $U_{m,i}$ shall be measured and transformed to the (full scale) reference speed $v_{tr,ref}$.

$$U_i = U_{m,i} \cdot \frac{v_{tr,ref}}{v_{tr,i}} \tag{18}$$

The characteristic air speed used for further analysis is the upper bound of a 2σ interval of the maximum resultant horizontal air speed during the whole passage

$$U_{95\%} = U_{2\sigma} = \overline{U} + 2 \cdot \sigma \tag{19}$$

where

$\overline{U}$ is the mean value over all measured maxima U_i;

σ is the standard deviation of all measured maxima U_i.

6.2.2.3 Numerical simulations

There are no agreed methods available.

6.2.2.4 Predictive formulae

There are no agreed formulae available.

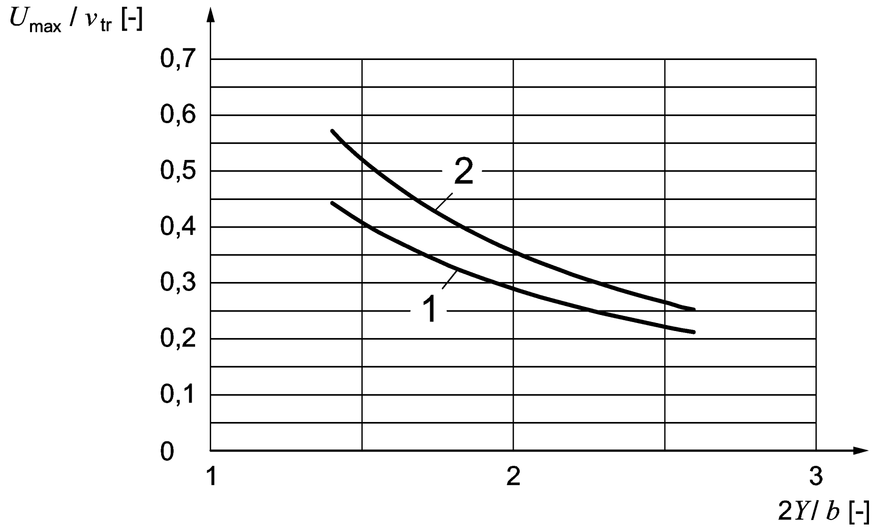
6.2.3 Slipstream effects on objects beside the track

Predictive formulae

The induced flow speed U is dependent on lateral distance, height and speed of the train as well as on the aerodynamic quality of the train. The maximum air velocities are approximately parallel to the track.

The maximum value, U_{max}, of U produced by a passing train is relevant for the loading of an object. Air velocity fluctuations might be relevant as well.

If results from measurements, calculations or simulations are not available, values U_{max}/v_{tr} as given in Figure 13 may be used as a rough estimate for passenger trains. The train induced air speeds are based on U_{max} measured at 1,50 m above top of rail and low pass filtered at 1 Hz.



Key

1 high speed train

2 loco hauled train

Figure 13 — Train induced air speeds

The load on an object is given by Formula (20):

$$F = C_F S \frac{\rho_0}{2} U_{max}^2 \qquad (20)$$

The relevant aerodynamic coefficients C_F may be measured in a wind tunnel test or taken from EN 1991-1-4. They are valid for objects with a lateral extent smaller than half the lateral distance to the train side.

6.3 Assessment of train-induced aerodynamic loads in the track bed

There are no normative methods available.

NOTE A test method for the measurement of aerodynamic loads in the track bed in connection with the assessment of ballast projection is described in Annex A (informative).

6.4 Assessment of resistance to motion

6.4.1 General

For a train travelling at constant speed on open track and zero wind conditions on straight and level track, the following formula relates the train's resistance to motion R_1 to the train speed v_{tr}:

$$R_1 = C_1 + C_2 v_{tr} + C_3 v_{tr}^2 \quad (21)$$

where

$C_1 + C_2 v_{tr}$ denotes both the mechanical resistance and the momentum drag due to air flow for traction and auxiliary equipment and the air conditioning systems;

$C_3 v_{tr}^2$ denotes the aerodynamic resistance due to pressure drag and skin friction drag.

6.4.2 Full-scale tests

6.4.2.1 General

For complete train sets, the most common approach to assess resistance to motion by full-scale tests is to carry out coasting tests.

A coasting test allows a determination of the speed dependent terms of R_1. For the C_1 term, a special test is needed, the most reliable being to haul the train at very low speed. The basic principle of a coasting test is to run the train up to a certain speed and then cease the tractive effort and all sources of magnetic resistance (e.g. insulated gate bipolar transistor – IGBT) before entering a test section. Instantaneous train speed and position are measured along the testing section. A recording of the train acceleration may also be needed depending on the method used. From this information, it is possible to estimate R_1 by fitting a theoretical curve to the experimental deceleration data. The major advantage of this methodology is that no measurement of the tractive effort is needed.

There are two different post-test data treatments commonly used to obtain the resistance to motion of a train from a coasting test:

— the regression method and;

— the speed history identification method.

The following subclauses deal with the hauling test requirements, the coasting test requirements and the post-test data treatment.

6.4.2.2 Requirements for train hauling procedure

A train hauling test consists of pulling the train at constant speed using a windlass. This test should be undertaken on a straight and level test section, for which the quality of both the geometry and the rail surface shall be as good as possible.

C_1 shall be determined via the mean tractive effort over a time interval for which the windlass speed is constant. In order to prevent the influence of speed dependent terms, the windlass speed shall be approximately 1 m/s.

The ambient wind speed shall be monitored and less than 2 m/s. Thus, the hauling test may practically be performed in a tunnel in order to minimize any wind influence.

Due to the effects of adhesion, coupling looseness, etc., the breakaway phase shall be avoided. The train mass shall be known with an accuracy of ± 2 % for mass correction purposes and the train axle-boxes shall be at the train operational temperature.

The uncertainty in C_1 determined from this test shall be lower than 10 %.

6.4.2.3 Requirements for coasting test procedure

If the regression method is to be used, the coasting test should be performed on test sections which are straight and level. The equivalent grade resistance, taking into account both gradients and curves, should be as low as possible compared to the resistance to motion. The previous requirement is not needed for the speed history identification post-test data treatments where grade and curve influence is taken into account in the post-test data treatments. For both post-test data treatments, it shall be ensured that the train under investigation can run at its maximum speed on the selected test section. Moreover, the detailed characteristics of the test section (slopes and curve radii) should be known precisely. If these characteristics are not easily available, an alternative method is to measure all three components of the acceleration by a dedicated accelerometer. Meteorological information, i.e. ambient wind speed, air pressure, humidity and temperature, shall be measured either on the test section or on the train exterior. It is essential that the location of the train relative to the track gradient, curve changes and meteorological station shall be known precisely. For example, a start and stop mark, readable by the train, may be used to determine the train's entrance and exit from the test section.

The train composition and mass, ideally in normal operational order (normal operational payload according to EN 15663), should be the same for each test. If not, the differences need to be taken into account when post-processing the data. The mass of the test train as well as the k factor accounting for the energy stored in the rotating masses shall be known with an accuracy of within ± 2 %. The k factor may be determined by coasting the train uphill with slow initial speed until the train comes to a stop. Axle-boxes shall be at their normal operational temperature. Furthermore, all cooling equipment shall have a well-defined and time-stable state, so as not to introduce bias into the measurements. The train shall be equipped with a velocity sensor, an odometer allowing train speed measurement with an accuracy of the greater of ± 1 % or ± 1 km/h.

Coasting tests should be performed from the maximum train speed $v_{tr,max}$ to zero. It is permissible to limit the test to the following speed range from $v_{tr,max}$ to $v_{tr,max}$ / 3. This reduced speed range may be achieved either in a single run or in a number of separate runs. If the latter approach is adopted, the train speed on entry into the test section should be varied in a stepwise manner, e.g. by steps of $v_{tr,max}$ / 20 over the speed range from $v_{tr,max}$ to $v_{tr,max}$ / 3. The relevant train measurements, i.e. speed, acceleration, etc., shall be recorded at a minimum sampling rate of 10 Hz. External events such as passing trains, tunnels, bridges or switches and crossings shall be carefully recorded by time and position. The data measured when passing these features should be excluded from the post-test data analysis. For the regression method, a minimum of three runs over the whole speed range is recommended, to assess the repeatability of the results and for the statistical analysis needed during the later analysis. For the speed history identification method, at least three runs should be performed from $v_{tr,max}$ to $v_{tr,max}$ / 3.

The main principle when analysing coasting test data is to respect the fundamental principle of dynamics:

$$km\gamma = -\left(R_1 + R_2\right) \tag{22}$$

where

k	is a factor accounting for the energy stored in rotating masses;
m	is the train mass;
γ	is the train acceleration measured during the coasting test;
R_2	is the equivalent curving and grade resistance.

The train acceleration γ can be measured directly during coasting tests or by calculating the derivative of speed between two time or track intervals. For the regression method, data affected by gradient changes shall be excluded from analysis. For both methodologies, data affected by switching off the tractive effort shall be excluded from analysis. Data acquired during the coasting test, e.g. train speed, acceleration, etc. should be low pass filtered. If the test section includes curves or slopes, the corresponding curving and grade resistances shall be taken into account as a part of the total resistance to motion. The equivalent curving and grade resistance is given by the following formula:

$$R_2 = \frac{m}{1\,000} \cdot g\left(i + \frac{r_r}{r}\right) \tag{23}$$

where

g is the acceleration due to gravity;

m is the train mass;

i is the gradient of the track in ‰;

r is the curve radius;

r_r is the reference curve radius of 800 m.

For each coasting test run, corrections shall be made for any differences in test train mass and meteorological conditions.

For the regression method, the resistance to motion is expressed in terms of the train speed using Formulae (21) to (23). An estimate of the coefficients C_1, C_2, and C_3 may be deduced by fitting a calculated curve to the measured data. In order to obtain a more physically realistic result, the C_1 coefficient shall be fixed to the mass corrected value derived from the train hauling test. The C_2 value should also be fixed using an assessment of the air momentum loss or a more sophisticated approach. A statistic which measures the goodness of fit of the calculated curve shall be defined. For the regression method, this indicator can be the regression coefficient. When using the regression method, it is necessary to ensure a uniform weighting of data when fitting the theoretical curve.

The speed history identification method is iterative and is based on the calculation of the coasting time t as a function of the train speed v_{tr}, using estimated resistance formulae. The parameters in the resistance formulae are adjusted until a good agreement between the calculated and the measured $v_{tr} \sim t$ diagrams is reached. A quality indicator shall be defined, e.g. the mean value of differences between calculated and measured speed on the full coasting test. The integral of $k\, m\, d\, v_{tr} / R_1$ which gives the coasting time between two speed values is calculated numerically. At each speed step, all the parameters affecting the resistance are adjusted so that a perfect simulation of the train run is made.

The mean values for R_1 and its standard deviations, as well as fixed values of $C_1$and C_2, if applied, shall be reported.

Annex A
(informative)

Procedure for full-scale tests regarding train-induced air flow in the track bed

A.1 General

Full-scale measurements may be used for train assessment and for risk analysis studies. All specified coordinates refer to the coordinate system specified in Figure 1.

A.2 Track configuration

This test procedure applies to standard gauge tracks (1 435 mm) or other gauge tracks with appropriate modifications. Tests shall be carried out on a straight and level track in open air.

There should be no obstacles in the test section and 100 m ahead and 20 m downstream of the test site. Infrastructure components, like switches and signalling equipment, beside the track and in the track bed, shall be avoided in the specified dimensions of the testing section. The layout of the chosen test site shall be recorded in detail. A flat ground configuration shall be achieved in the test section between the rails. This configuration should be achieved by introducing several cover plates between the rails.

A ground configuration comprises plates with a smooth surface with a defined sand grain roughness below 2 mm. The upper surface should be in the range of z = 175 mm ± 5 mm (below top of rail). Gaps between cover plates should be avoided. All gaps shall be covered, i.e. by slats with a max. height of 4 mm and a max. length of 80 mm.

The plates should completely cover the space between rails within sleeper bays with a max. length of the cut-outs per sleeper on both sides of $\Delta x \leq 300$ mm. The central part of the track should be completely covered and smooth over a minimum total width of $\Delta y \geq 750$ mm.

Disturbances by fixation elements for the plates should be avoided. Fixation elements should not extend further than 100 mm from the rail foot to the centre of the track.

There shall be at least 20 m of the flat ground configuration ahead of the first installed sensor and at least 5 m behind the last sensor, regarding the train passage direction. A spacing of at least 5 m shall be matched between subsequent sensors.

Plates used for covering individual sleeper bays should withstand a 50 kg test weight positioned on its centre with a maximum vertical displacement of 15 mm. Increased stability may be necessary to withstand train induced loads.

Track sensors shall be placed at z = 25 mm (below top of rail) at the track centre y = 0 m and at y = ± 0,2 m. The sensors can be separated longitudinally. The uncertainty of sensor positions shall be less than 5 mm in lateral and less than 2 mm in vertical direction. The actual position of the sensors shall be recorded and documented.

A.3 Vehicle configuration and test conditions

Tests should be carried out with the longest possible train configuration and vertical ground clearance corresponding to standard operational conditions. The vertical ground clearance should be documented for representative parts of the underframe. Ventilation devices with air flows directed towards the track bed should be operated in maximum operational condition. For non-symmetrical train compositions the tests should be carried out in both running directions.

The investigated train shall be correctly identified at the test site and its composition shall be documented. The nominal test speed should be the maximum speed of the train.

A.4 Instrumentation and data acquisition

The meteorological conditions (air temperature, air pressure, air humidity, wind speed and direction with respect to the track) shall be measured. Acquisition shall comply with ISO 8756. For each test run, the ambient wind speed should not exceed 3 m/s. The wind speed component parallel to the track shall not exceed 2 m/s. The wind speed and direction are determined by a meteorological station installed at y = 4 m ± 0,25 m and z = -2 m ± 0,25m, preferably at the beginning of the test section. The wind speed is equivalent to the mean wind speed in the 3 s interval ranging from 4 s to 1 s before the first axle passes the wind sensor. The temperature used to compute the ambient air density shall be measured at a representative position in the track. Precipitation should be avoided for valid measurements.

The airflow measurement shall start at least 1 s before the first train axle passes the first sensor and continue until at least 10 s after the last axle has passed the last sensor. The x-component of the airflow is of major interest. The used sensor should resolve 100 Hz fluctuations in flow correctly. The noise-to-signal ratio shall be less than 3 % based on the maximum measured signal amplitude or noise shall be shown to have less than 1 % impact on the assessment quantity. The sensors should allow a measurement range of at least 60 m/s and shall be sampled at least with 200 Hz. If applicable, eigenfrequency of sensors shall be above 150 Hz.

Following sensor types are recommended to carry out the measurements:

— static Pitot tubes;

— Pitot tubes with separate static pressure ports in the ground plate;

— 1-, 2- or 3-dimensional ultra-sonic anemometers.

The tests shall consist of at least 20 independent and comparable test samples. All measurements shall be taken within ± 5 % of the nominal test speed and the measured average acceleration of the train shall be less than ± 0,15 m/s^2 for valid data. The train speed and train acceleration shall be measured by means of a pair of rail mounted axle counters or light barriers.

The uncertainty of any pressure based measurements shall not exceed ± 3 % of the maximum measured output. For air flow measurements the uncertainty shall not exceed ± 1,5 % correspondingly. The uncertainty of train speed measurement shall not exceed ± 1 % of the nominal test speed. The average acceleration shall be determined during the passage of all train axles over the test section from the recorded axle spacings with an accuracy of at least 0,1 m/s^2. The local ambient air density shall be determined with an accuracy of at least ± 1,5 %.

A.5 Data processing

From the measured data an assessment quantity or risk parameter may be calculated that indicates the performance of the tested vehicle. There are three different proposed assessment quantities of different complexity defined to describe the aerodynamic loads on the track:

— mean load and standard deviation in conjunction with SSIA (Stress-Strength Interference Analysis; $M\sigma$ parameter);

— Risk Indicator RI from Ballast Speed predicted with a Simple integration method (RIBSS);

— parameters resulting from the Stochastic Particle Method (SPM).

Details for the proposed assessment approaches can be found in [10].

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