



BSI Standards Publication

Railway applications — Aerodynamics

Part 6: Requirements and test procedures for cross wind assessment

National foreword

This British Standard is the UK implementation of EN 14067-6:2018+A1:2022. It supersedes BS EN 14067-6:2010, which is withdrawn.

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The UK participation in its preparation was entrusted to Technical Committee RAE/1/-/4, Railway Applications - Aerodynamics.

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Published by BSI Standards Limited 2022

ISBN 978 0 539 14175 7

ICS 45.060.01

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This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 August 2018.

Amendments/corrigenda issued since publication

Date	Text affected
31 October 2022	Implementation of CEN amendment A1:2022

English Version

Railway applications - Aerodynamics - Part 6: Requirements and test procedures for cross wind assessment

Applications ferroviaires - Aérodynamique - Partie 6 :
Exigences et procédures d'essai pour l'évaluation de la
stabilité vis-à-vis des vents traversiers

Bahnanwendungen - Aerodynamik - Teil 6:
Anforderungen und Prüfverfahren zur Bewertung von
Seitenwind

This European Standard was approved by CEN on 3 March 2018 and includes Amendment 1 approved by CEN on 6 June 2022.

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CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

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European foreword

This document (EN 14067-6:2018+A1:2022) 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of an identical text or by endorsement, at the latest by January 2023, and conflicting national standards shall be withdrawn at the latest by January 2023.

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

This document includes Amendment 1 approved by CEN on 6 June 2022.

This document supersedes A1 EN 14067-6:2018 A1.

The start and finish of text introduced or altered by amendment is indicated in the text by tags A1 A1.

This European Standard is part of the series “Railway applications — Aerodynamics” which consists of the following parts:

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

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

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Introduction

Trains running on open track are exposed to cross winds. The cross wind safety of railway operations depends on vehicle and infrastructure characteristics and operational conditions. Important parameters are:

- aerodynamic characteristics of the vehicle;
- vehicle dynamics (e.g. mass, suspension, bump stops);
- track gauge;
- line characteristics (radius and cant of the track, height of embankments and bridges, walls near the track);
- wind exposure of the line;
- operating speed, mode of operation (non-tilting, tilting, running direction).

1 Scope

This document gives guidelines for the cross wind assessment of railways.

This document is applicable to all passenger vehicles, locomotives and power cars (with a maximum train speed above 140 km/h up to 360 km/h) and freight wagons (with a maximum train speed above 80 km/h up to 160 km/h) and track gauges from 1 435 mm to 1 668 mm inclusive. For passenger vehicles, locomotives and power cars with a maximum train speed between 250 km/h and 360 km/h, a requirement to demonstrate the cross wind stability is imposed. This document is not applicable to light rail and urban rail vehicles.

2 Normative references

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

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

EN 14363, *Railway applications - Testing and Simulation for the acceptance of running characteristics of railway vehicles - Running Behaviour and stationary tests*

EN 15663, *Railway applications - Vehicle reference masses*

3 Terms and definitions

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

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

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

3.1 bias

systematic error affecting an estimate

Note 1 to entry: In this document, it is expressed as the ratio of a coefficient obtained during benchmark wind tunnel tests to the equivalent coefficient obtained during new wind tunnel tests.

3.2 coordinate system

system denoting the axis for forces, moments, dimensions and wind speeds as defined in Figure 1

Note 1 to entry: The coordinate system is shown in Figure 1.

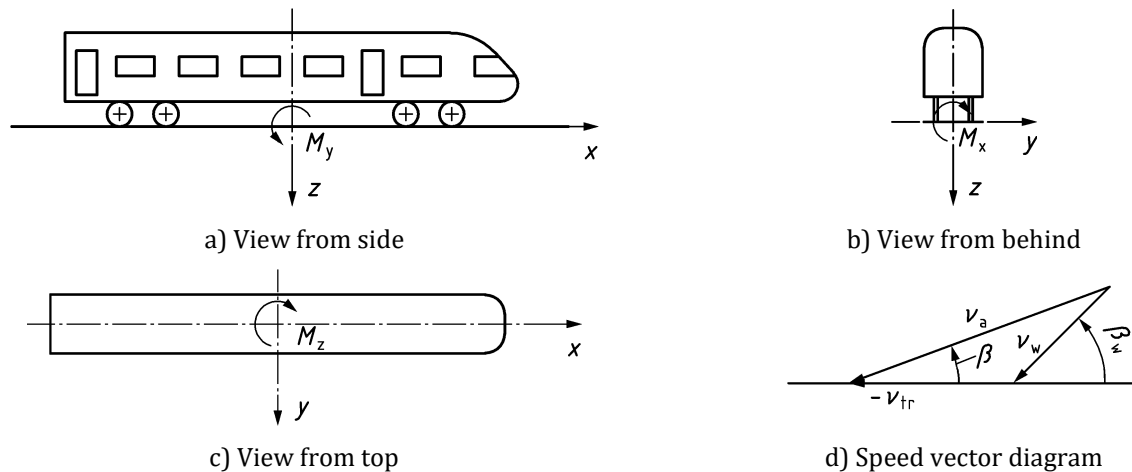


Figure 1 — Coordinate system

Note 2 to entry: A positive β means that the apparent wind v_a is coming from the right hand side of the train.

3.3

lee rail

rail on the side of the track that is away from the direction from which the wind is blowing

4 Symbols and abbreviations

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

Table 1 — Symbols and abbreviations

Symbol	Unit	Significance	Explanation or remark
A	m^2	Reference area	
A_0	m^2	Reference normalization area	10 m^2
A^*	-	Constant in formula for σ_u	
$\tilde{A}$	-	Normalized gust amplitude	
$\underline{A}_{ij}$	-	Rotation matrix from B_j to B_i	
a	m	Bogie semi-spacing	
a_{ij}	N	Wheel loads	$i = 1, 2$: (front, back) $j = 1, 2$: (right, left)
a_m	s/m	Dispersion	Dispersion determined by extreme value analysis of wind tunnel data
a_q	m/s^2	Uncompensated lateral acceleration; also equivalent to cant deficiency	$a_q = \frac{v_{tr}^2}{R_c} - \frac{gH_{cant}}{2b_A}$
a_{q-max}	m/s^2	Maximum value of uncompensated lateral acceleration	
B_E	-	Embankment blockage ratio	The ratio of the height of the tallest

Symbol	Unit	Significance	Explanation or remark
			model embankment to the free height of the wind tunnel
B_V	-	Vehicle blockage ratio	The ratio of the total model vehicle reference area to the wind tunnel free cross-sectional area
b	-	Coefficient function of $\tilde{r}_g$	
b_A	m	1/2 lateral contact spacing	See 5.4.2.3
$b_{A,min}$	m	Minimum lateral contact spacing	
b_1	m	y position of right secondary suspension spring	
b_2	m	y position of left secondary suspension spring	
C	-	Coherence function for the resulting wind speed	
C_{90}	-	Coherence function for a wind angle of 90°	
$C_{(z0)}$	-	Function of roughness length in definition of longitudinal integral length scale	
CWC		Characteristic wind curve	
CWC_i	m/s	Evaluation of the stochastic CWC wind speed	
c	m/s	Speed of sound	
c_{Fi}	-	Force coefficient based on A_0	$c_{Fi} = \frac{2 \cdot F_i}{\rho \cdot v^2 A_0}, i = x, y, z$
c_M	-	Moment coefficient based on A_0 and d_0	$c_{Mi} = \frac{2 \cdot M_i}{\rho \cdot v^2 A_0 d_0}, i = x, y, z$
$c_{Mx,lee}$	-	Rolling moment coefficient around lee rail	
$\bar{c}_{Mx,lee}$	-	Mean rolling moment coefficient around lee rail	
$\hat{c}_{Mx,lee}$	-	Peak rolling moment coefficient around lee rail	
$c_{Mx,lee,bmk}$	-	Benchmark value of rolling moment coefficient around lee rail	Rolling moment coefficient determined from the benchmark tests
$\hat{c}_{Mx,lee,bmk}$	-	Benchmark value of peak rolling moment coefficient around lee rail	
$c_{Mx,lee,test}$	-	Measured test results for rolling moment coefficient around lee rail for benchmark vehicle	

Symbol	Unit	Significance	Explanation or remark
$\hat{c}_{M_{x,lee}, m}$	-	Peak rolling moment coefficient around lee rail uncorrected for bias	
$\bar{c}_{M_{x,lee}, m}$	-	Mean measured rolling moment coefficient around lee rail uncorrected for bias	
$c_{s\phi, i}$	Nm	Torsion suspension constant	
c_u	-	Coefficient in the Cooper theory	
c_v	-	Coefficient in the Cooper theory	
$c_{y,BGi}$	m	y position of bogie i in local coordinates (centre of gravity)	$i = 1$: front bogie, $i = 2$: rear bogie
$c_{z,BGi}$	m	z position of bogie i in local coordinates (centre of gravity)	$i = 1$: front bogie, $i = 2$: rear bogie
$c_{x,CB}$	m	x position of car body in local coordinates (centre of gravity)	
$c_{y,CB}$	m	y position of car body in local coordinates (centre of gravity)	
$c_{z,CB}$	m	z position of car body in local coordinates (centre of gravity)	
$c\theta$	-	$\cos(\Theta_{Bi})$	
$c\phi$	-	$\cos(\Phi_{Bi})$	
$c\psi$	-	$\cos(\Psi_{Bi})$	
d	m	Characteristic length	3 m
d_0	m	Reference normalization length	3 m
$\underline{dr}_{kpi}$	m	Deflection of the i primary spring	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{dr}_{cpj,i}$	m	Deflection of the j primary spring	$j = 1$ (right), 2 (left). $i = 1$: front bogie, $i = 2$: rear bogie
$\underline{dr}_{csj,i}$	m	Deflection of the j secondary spring	$j = 1$ (right), 2 (left). $i = 1$: front bogie, $i = 2$: rear bogie
$d\phi_{cs,i}$	rad	Rotation angle of the bogie anti-roll bar	$i = 1$: front bogie, $i = 2$: rear bogie
F_i	N	Aerodynamic force	
$F_i(t)$	N	Aerodynamic force	Time dependent version of F_i
F_x F_y F_z	N	Aerodynamic forces in the directions of coordinates	
f	Hz	Wind frequency	
f_{gust}	Hz	Characteristic gust frequency	

Symbol	Unit	Significance	Explanation or remark
f_{BL}	-	Blockage correction factor	Function of x_B
$\underline{f}_{ci}$	N	Spring force vector of primary and secondary spring	$i = 1$: front bogie, $i = 2$: rear bogie
$f_{ci,x}$	N	Spring force of primary and secondary springs in x direction	$i = 1$: front bogie, $i = 2$: rear bogie
$f_{ci,y}$	N	Spring force of primary and secondary springs in y direction	$i = 1$: front bogie, $i = 2$: rear bogie
$f_{ci,z}$	N	Spring force of primary and secondary springs in z direction	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{f}_{cpj,i}$	Nm	Primary suspension constant	$i = 1, 2$: (front, back) $j = 1, 2$: (right, left)
$\underline{f}_{csj,i}$	Nm	Secondary suspension constant	$i = 1, 2$: (front, back) $j = 1, 2$: (right, left)
f_{emb}	-	Embankment speed up factor	
$\underline{f}_{f,Bi}$	N	Spring force vector of primary and secondary springs on body Bi	$i = 1$: front bogie, $i = 2$: rear bogie
$f_{f,BGi}$	N	Suspension force on bogie i	
$\underline{f}_{f,CB}$	N	Spring force vector of primary and secondary springs on car body	
$f_{f,WSi}$	N	Suspension force on wheel set i	
f_h	-	Function of the embankment blockage ratio, B_E	
$f_{\Delta Q}$	-	Relative windward wheel unloading factor	0,9
f_L	-	Function of vehicle length	
f_m	-	Method factor	To account for uncertainties in the 3-mass model.
$\underline{f}_{m,Bi}$	N	Mass force vector on body Bi	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{f}_{m,CB}$	N	Mass force vector on car body	
f_n	Hz	n-frequency	$f_n = \frac{\omega_n}{2\pi} = \frac{n\omega_0}{2\pi}$
f_{smp}	Hz	Data acquisition frequency	The sampling frequency (rate) for acquiring data in the wind tunnel
$\underline{f}_{total,Bi}$	N	Total force vector acting on body Bi	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{f}_{total,BGi}$	N	Total force vector acting on bogie i	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{f}_{total,CB}$	N	Total force vector acting on car body	

Symbol	Unit	Significance	Explanation or remark
$\underline{f}_{\text{total,WSi}}$	N	Total force vector acting on wheel set i	
f_u	-	Normalized wind frequency	
$\tilde{f}_u$	-	Normalized wind frequency in the Cooper theory	
$\hat{f}_u$	-	Normalized wind frequency in the Cooper theory	
$\tilde{f}_v$	-	Normalized wind frequency in the Cooper theory	
$\hat{f}_v$	-	Normalized wind frequency in the Cooper theory	
$\underline{f}_{\text{Wi,CB}}$	N	Wind force acting on car body	
G	-	Gust factor	
g	m/s ²	Acceleration due to gravity	
H	-	Aeroadmittance function in Cooper theory	
H_{cant}	m	Cant height	
h	m	Vehicle height	
h_2	m	Vertical position vector component	
h_{BL}	m	Boundary layer height	
h_z	m	Height from ground	
h_{z0}	m	Roughness height	
h_{VEH}	m	Height of the vehicle from top of rail to roof	
I_i	-	Turbulence index for the i -wind component	$i = u, v, w$
$I_u(z)$	-	Turbulence intensity	The standard deviation of the wind tunnel velocity at height z divided by the mean velocity at that height
k_p	N/m	Primary spring stiffness	
k_s	N/m	Secondary spring stiffness	
$k_{\text{standstill}}$	-	Dimensionless characteristic wind speed for a vehicle at standstill	
k_v	-	Vehicle blockage factor	Correction factor applied to the mean or peak wind tunnel velocity to allow for the effects of the constraints of the tunnel walls on the local flow over the vehicle

Symbol	Unit	Significance	Explanation or remark
$\bar{k}_e$	-	Mean wind embankment blockage factor	Correction factor applied to the mean wind tunnel velocity to allow for the effects of the constraint of the wind tunnel roof on the flow over the embankment
$\hat{k}_e$	-	Peak wind embankment blockage factor	Correction factor applied to the peak wind tunnel velocity to allow for the effects of the constraint of the wind tunnel roof on the flow over the embankment
$\bar{k}_{Mx,bias}$	-	Mean bias correction factor	
$\hat{k}_{Mx,bias}$	-	Peak bias correction factor	
L	m	Vehicle length	
L_i	m	Compound turbulence length scale of the i wind component	$i = u, v$
L_0	m	Reference length	25 m
L_{VEH}	m	Length parameter of the vehicle body	Length of the vehicle body without buffer and inter car gap
L_X	m	Wind tunnel streamwise turbulence length scale at 3 m equivalent height	
$L_{X,FS}$	m	Full scale longitudinal turbulence length scale	
r_{L_u}	-	Non-dimensional compound length scale of the wind component	
$^x L_i$	m	Longitudinal integral length scale of the i -wind velocity component along the x direction	$i = u, v, w$
$^x L_u$	m	Turbulence length scale	Longitudinal streamwise velocity turbulence length scale in the core stream
$^y L_u$	m	Turbulence length scale	
$^x L_v$	m	Turbulence length scale	
$^y L_v$	m	Turbulence length scale	
$^y L_i$	m	Lateral integral length scale of the i -wind velocity component along the y direction	$i = u, v, w$
$^x L_{u_FS}$	m	Full scale turbulence length scale	
L_u^y	m	Characteristic length (spatial wavelength) of the gust	
$\tilde{L}_u$	-	Normalized turbulence length scale	

Symbol	Unit	Significance	Explanation or remark
$\tilde{L}_v$	-	Normalized turbulence length scale	
Ma	-	Mach number: Ratio of wind speed over speed of sound	Ma = U/c
M_{CoG}	Nm	Moment due to the lateral movement of the centre of gravity of suspended masses	
M_i	Nm	Aerodynamic moment	$i = x, y, z$
M_{la}	Nm	Moment due to uncompensated lateral acceleration	
M_m	Nm	Restoring moment due to the vehicles masses	
M_x	Nm	Aerodynamic rolling moment	See 3.3
$M_{x,lee}$	Nm	Rolling moment around lee rail	On top of the lee rail with distance b_a to centre of track
$\bar{M}_{x, lee}$	Nm	Mean rolling moment	The mean vehicle aerodynamic rolling moment around the lee rail in an atmospheric boundary layer wind tunnel
$\hat{M}_{x,lee}$	Nm	Peak rolling moment	A statistical estimate of the peak vehicle aerodynamic rolling moment around the lee rail that would occur with a specified probability of exceedances within a specified period
M_y	Nm	Aerodynamic pitching moment	See 3.3
M_z	Nm	Aerodynamic yawing moment	See 3.3
m	kg	Vehicle mass (to be considered for cross wind assessment)	Refers to operational mass in working order according to EN 15663 but without wear allowances.
m_0	kg	Unsprung masses	Refers to operational mass in working order according to EN 15663 but without wear allowances.
m_1	kg	Primary suspended masses	Refers to operational mass in working order according to EN 15663 but without wear allowances.
m_2	kg	Secondary suspended masses	Refers to operational mass in working order according to EN 15663 but without wear allowances.
m_{Bi}	kg	Mass of body Bi	

Symbol	Unit	Significance	Explanation or remark
$\bar{N}$	-	Number of evaluations of the stochastic CWCs	
n	Hz	Generic harmonic component of the wind speed spectrum	
$n_{\max}$	-	Number of harmonics considered in the series representation of $U_{TC}(t)$	
$P(\hat{U}_m)$	-	Cumulative probability of each $\hat{U}_m$	
$Pr(T)$	-	Probability of a wind gust of duration T seconds	
ΔQ	N	Wheel unloading	
Q_{target}	N	Target value of wheel unloading	
Q_0	N	Average static wheel load	
Q_{i1}	N	Q-forces of the unloaded wheel of the first wheel set in the bogie	
Q_{j1}	N	Q-forces of the unloaded wheel of the second wheel set in the bogie	
$Q_{1,WSi}$	N	Wheel-rail-forces	
$Q_{2,WSi}$	N	Wheel-rail-forces	
$\Delta Q/Q_0$	-	Relative wheel unloading	
R	mm	Radius of edge of ballast and rail ground board	
R_C	m	Radius of curve	
Re	-	Reynolds' number: ratio of inertia forces over viscous forces	$Re = \frac{U_{\text{test}} d}{\nu}$
$Re_{\max}$	-	Maximum Reynolds' number	The maximum achievable Reynolds' number in a wind tunnel test
r_0	m	z position of wheel set i in local coordinates	
$\tilde{r}_g$	m	Non-dimensional separation distance	
$\underline{r}_{CBi,Bi}$	m	Position vector of centre of gravity of body i	
$\underline{r}_{CBi,I}$	m	Position vector of centre of gravity of body i in the stationary global reference system	
$\underline{r}_{CBGi,BGi}$	m	Position vector of centre of gravity of bogie i	
$\underline{r}_{CCB,CB}$	m	Position vector of centre of gravity of car body	

Symbol	Unit	Significance	Explanation or remark
$\underline{r}_{CP1,BGi}$	m	Position vector of primary suspension on bogie i , right spring	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{r}_{CP2,BGi}$	m	Position vector of primary suspension on bogie i , left spring	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{r}_{CP1,WSi}$	m	Position vector of right primary spring on wheel set i	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{r}_{CP2,WSi}$	m	Position vector of left primary spring on wheel set i	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{r}_{CS1,BGi}$	m	Position vector of secondary suspension on bogie i , right spring	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{r}_{CS2,BGi}$	m	Position vector of secondary suspension on bogie i , left spring	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{r}_{CS1,BGi,CB}$	m	Position vector on the car body of the secondary suspension on bogie i , right spring	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{r}_{CS2,BGi,CB}$	m	Position vector on the car body of the secondary suspension on bogie i , left spring	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{r}_{CWSi,WSi}$	m	Position vector of centre of gravity of wheel set i	$i = 1$: front bogie, $i = 2$: rear bogie
S_{ii}	$m^2/s^2/H$ z	Wind speed power spectral density for the i -wind velocity component	$i = u, v, w$
S_t	-	Model time scale	The ratio of time at model scale to time at full scale
$S_u(n)$	$m^2/s^2/H$ z	Power spectral density of u	n is the frequency
SY_{WSi}	N	Sum of Y-forces	$i = 1$: front bogie, $i = 2$: rear bogie
$\tilde{S}_{uTuT}$	-	Non-dimensional power density function	
$\tilde{S}_{vTvT}$	-	Non-dimensional power density function	
s^Θ	-	$\sin(\Theta_{Bi})$	
s^Φ	-	$\sin(\Phi_{Bi})$	
s^Ψ	-	$\sin(\Psi_{Bi})$	
T	s	Time duration of a gust	
$\bar{T}$	s	Mean time constant of a gust	
T_{samp}	s	Data acquisition duration	The sampling duration for acquiring data

Symbol	Unit	Significance	Explanation or remark
Tu_x		Turbulence level	$Tu_x = \left(\overline{U(t)}^2 / \overline{U_{test}}^2 \right)^{0,5}$
t	s	Time	
$\underline{t}_{es,i}$	Nm	Anti-roll bar moment vector	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{t}_{CBGi}$	Nm	Torsion suspension moments on bogie i	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{t}_{CB}$	Nm	Torsion suspension moments on the car body	
$\underline{t}_{WSi}$	Nm	Torsion suspension moments on wheel set i	$i = 1$: front bogie, $i = 2$: rear bogie
t_i	s	Event times during the Chinese hat gust	$i = 1, 2..7$
$\underline{t}_{m,Bi}$	Nm	Mass forces on body i	
$\underline{t}_{m,CB}$	Nm	Mass forces on car body	
$\underline{t}_{total,Bi}$	Nm	Total moment vector for body i	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{t}_{total,CB}$	Nm	Total moment vector for car body	
$\underline{t}_{total,BGi}$	Nm	Total moment vector for bogie i	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{t}_{total,WSi}$	Nm	Total moment vector for wheel set i	$i = 1$: front bogie, $i = 2$: rear bogie
$\underline{t}_{Wi,CB}$	Nm	Wind forces on the car body	
U	m/s	Wind speed	
$\bar{U}$	m/s	Mean wind tunnel velocity	Mean wind tunnel velocity after correction for blockage effect. For further definitions of U_{mean} see Annex B and Annex G.
U_{max}	m/s	Maximum wind speed in the Chinese hat gust	
U_{mean}	m/s	Mean wind speed	Refers to the upwind at 4 m height above ground
U_{normal}	m/s	Normal component of wind upstream of an embankment	
$U_{parallel}$	m/s	Parallel component of wind upstream of an embankment	
$U(t)$	m/s	Instantaneous wind (tunnel) velocity	
u_{turb}	m/s	Wind velocity turbulent component along the mean wind direction	
$U_T(t)$	m/s	Wind velocity component perpendicular to the direction of track seen by a moving point	
$U_T(f_n)$	m/s	Generic harmonic of wind speed spectrum S_{uTuT}	

Symbol	Unit	Significance	Explanation or remark
$U_{TC}(t)$	m/s	Transverse component of the corrected absolute wind speed seen by a moving $\bar{U}_{raw}$ point	
$U_{TC}(f_n)$	m/s	Generic harmonic of $U_{TC}(t)$	
$\bar{U}_{test}$	m/s	Mean wind tunnel speed during a test	
$\bar{U}_m$	m/s	Uncorrected measured value of mean wind tunnel velocity	
$\bar{U}_{e,m}$	m/s	Uncorrected measured value of mean wind tunnel velocity above an embankment	
$\bar{U}_{ref}$	m/s	Mean wind tunnel reference wind speed	Used as the target when testing, actual speed during a test might be different
$\bar{U}_{FS}$	m/s	Full scale mean wind	
$\hat{U}_m$	m/s	Uncorrected peak wind tunnel velocity	Peak wind tunnel velocity determined by a Lieblein analysis
$\hat{U}_{e,m}$	m/s	Uncorrected peak wind tunnel velocity over the embankment	A statistical estimate of the peak measured wind tunnel velocity over the embankment that would occur with a specified probability of exceedance in a specified period
$\hat{U}_j$	m/s	Ranked peak wind tunnel velocity values	Obtained from 12 blocks of 10 minutes equivalent full scale data, $j = 1, \dots, 12$
$\bar{U}_{m,z}$	m/s	Uncorrected mean wind tunnel velocity at height z	The mean value of the measured wind tunnel velocity within a data acquisition period at an equivalent height z
$\bar{U}_{1_s}$	m/s	Running one second average wind tunnel wind speed	
u	m/s	Mode of $\hat{U}_j$ values	Mode obtained by extreme value analysis of wind tunnel data
$u(t)$	m/s	Chinese hat time wind speed variation	
u_x	m/s	Wind velocity of the u-component along the track (gust modelling)	
u_y	m/s	Wind velocity of the u-component across the track (gust modelling)	
V_{emb}	m/s	Wind velocity on an embankment	Used in the embankment overspeed effect
$V_{rel,TC}(t)$	m/s	Corrected relative wind velocity	
V_{rel}	m/s	Velocity in the Cooper theory	

Symbol	Unit	Significance	Explanation or remark
v_{turb}	m/s	Wind velocity turbulent component perpendicular to the mean wind direction	
$v_T(f_n)$	m/s	Generic harmonic of wind speed spectrum $S_{v_{\text{TVT}}}$	
$v_T(t)$	m/s	Wind velocity component along the direction of the track seen by a moving point	
v_W	m/s	Wind speed	Wind speed measured at stationary point
v_{W-90}	m/s	Wind speed normal to the track	
v_a	m/s	Relative wind velocity	Resultant wind speed acting on the vehicle
v_{max}	m/s	Maximum train speed	
v_{tr}	m/s	Train speed	
w	-	Wind vector	In x-y plane
$w_{\text{standstill}}$	m/s	Characteristic vehicle wind speed for overturning at standstill	
x y z	m	Cartesian coordinates	See 3.3 x : Origin is halfway between the axles of the inner wheels y : Origin is track centre line z : Origin is top of rail
X Y Z		Coordinate axis of global reference systems	
x_B	%	Blockage ratio at $\beta = 30^\circ$	Total modelled configuration projected side area to the wind tunnel cross-sectional area
x_{Bi}	m	x position of body i	
$\underline{x}$	m	Position vector of vehicle system 5-mass model	
$\underline{x}_{Bi}$	m	Position vector of body i	
$\underline{x}_{BGi}$		Position vector of bogie i	
$\underline{x}_{CB}$	m	Position vector of a car body	
$\underline{x}_{WSi}$	m	Position vector of wheel set i	
$\tilde{x}$	m	Spatial distance to the maximum gust amplitude	

Symbol	Unit	Significance	Explanation or remark
y_B	m	(Maximum) displacement of the contact point on the wheel in the wheel flange direction	
y_{Bi}	m	y position of body i	
y_{BGi}	m	Bogie i displacement in y direction	
y_{CB}	m	Car body displacement in y direction	
y_1	m	Primary mass lateral displacement	See Figure 4
y_2	m	Secondary mass lateral displacement	See Figure 4
z_{Bi}	m	z position of body i	
z_{BGi}	m	Bogie i displacement in z direction	
z_{CB}	m	Car body displacement in z direction	
z_{CoG}	m	Height of the centre of gravity of the total vehicle	
$z_{CoG,0}$	m	Height of the centre of gravity of the unsprung masses	
$z_{CoG,1}$	m	Height of the centre of gravity of the primary suspended masses	
$z_{CoG,2}$	m	Height of the centre of gravity of the secondary suspended masses	
β	°	Yaw angle	The angle between the vehicle axis and the relative wind acting on the train. In a wind tunnel with stationary train model, it is the angle between the train axis and the wind tunnel axis.
β_W	°	Wind angle to track	The angle between the wind direction and the forward direction of the train
β_{Wi}	°	Wind angle to track in decomposition method	
$\tilde{\beta}$	°	Modified yaw angle	
γ_{ii}	-	Square root of the coherence function of the i -wind velocity component	$i = u, v, w$
$\delta_{99\%}$	m	Boundary layer thickness	z coordinate at which the local velocity equals 99 % of the free stream velocity
Δn	Hz	Frequency resolution	1/300 Hz
Δt	s	Equivalent time in an atmospheric boundary layer wind tunnel of 1 s of time at full scale	
Δv_{tr}	m/s	Train speed increment	

Symbol	Unit	Significance	Explanation or remark
$\varepsilon_{\max}$	-	Maximum tolerance target value	
$\varepsilon_{\text{mean}}$	-	Mean tolerance target value	
Θ_{Bi}	rad	Angle of rotation of the body i around the y-axis	
Θ_{CB}	rad	Angle of rotation of the car body around the y-axis	
k	-	Kármán constant	0,4
ν	m ² /s	Kinematic viscosity	
ρ	kg/m ³	Air density in the wind tunnel test	
ρ_0	kg/m ³	Reference air density	$\rho_0 = 1,225 \text{ kg/m}^3$
Σm	Nm	Moment of equilibrium around the lee rail	
σ	m/s	Standard deviation of the stochastic CWC wind speeds	
σ_u	m/s	Standard deviation of the u-wind velocity component	
σ_v	m/s	Standard deviation of the v-wind velocity component	
Φ_{Bi}	rad	Rotation of the body i around the z axis	
Φ_{CB}	rad	Rotation of the car body around the z axis	
Ψ_{Bi}	rad	Rotation of the body i around the x-axis	
Ψ_{CB}	rad	Rotation of the car body around the x-axis	
Ψ_{BGi}	rad	Rotation of bogie i around the x-axis	$i = 1$: front bogie, $i = 2$: rear bogie
ω_0	1/s	Fundamental frequency	

5 Methods and requirements to assess cross wind stability of vehicles

5.1 General

This clause presents various methods to assess the cross wind stability of railway vehicles.

The basic principle is that the cross wind stability of rolling stock is given by values of characteristic wind speeds that the rolling stock can withstand before exceeding some wheel unloading limit values. When these characteristic wind speeds are listed for varying input parameters such as train speeds, uncompensated lateral accelerations or wind angles to the track, the resulting set of characteristic wind speeds is called the characteristic wind curves (CWCs).

The cross wind stability of a train is given by the cross wind stability of the most cross wind sensitive vehicle in the train consist. Argumentation shall be provided taking into account aerodynamic and major vehicle parameters.

It is noted that the CWCs indicate the cross wind stability of the train related to a characteristic state of the wheel vertical forces; the characteristic wind curves do not indicate an overturning threshold.

For a given train running at a range of speeds, the CWCs define the maximum wind speed with a given direction to track that a train can withstand before a characteristic limit for wheel unloading is exceeded. The criterion that defines the CWC is the average value of wheel unloading, ΔQ , of the most critical running gear. The term “average” means that, in case of bogies, wheel unloading is averaged over the wheel sets of the bogie. For the relative assessment of cross wind stability of vehicles the reference air density ρ_0 is fixed at 1,225 kg/m³. Further, the vehicle mass to be considered is defined as the “operational mass in working order” according to EN 15663, except that it is required to calculate without wear allowances (e.g. discs, brake pads, wheels, etc.).

The assessment of cross wind stability of vehicles separates into evaluations of the aerodynamic characteristics (i.e. the aerodynamic coefficients) and the vehicle dynamic characteristics.

5.2 states the applicability of the various methods for the purpose of rolling stock assessment.

5.3 provides various methods for the determination of aerodynamic coefficients of passenger and freight vehicles and locomotives.

5.4 provides various methods for the determination of wheel unloading.

5.5 gives information on the required presentation form of CWCs of passenger and freight vehicles and locomotives.

5.6 provides requirements for rolling stock.

5.2 Applicability of cross wind methodologies for rolling stock assessment purposes

5.3 and 5.4 provide various methods for the assessment of the aerodynamic and vehicle dynamic characteristics. In general, these methods divide into simple and complex methods. The simpler methods are easier to apply, but imply an extra uncertainty supplement because they are tuned to be conservative in comparison to the complex ones.

Table 2 specifies which method shall be applied for rolling stock assessment purposes depending on the type of rolling stock and its maximum speed $v_{\max}$.

If various methods are permitted, the choice of the method depends on the degree of accuracy necessary for the problem. As a general principle, however, it is logical to start with the simplest appropriate procedures and then to shift to more complex methods if necessary.

All vehicles shall be assessed using any of the methods in Table 2.

For a fixed train composition it is sufficient to prove the cross wind stability of only the most cross wind sensitive vehicle in the train consist. In other cases, it is necessary to prove the cross wind stability of each vehicle.

Table 2 — Application of cross wind methodologies for rolling stock assessment

	Passenger rolling stock and locomotives			Freight wagons	
Speed range	$v_{\max} \leq 140 \text{ km/h}$	$140 \text{ km/h} < v_{\max} \leq 200 \text{ km/h}$	$200 \text{ km/h} < v_{\max} \leq 360 \text{ km/h}$ ^a	$v_{\max} \leq 80 \text{ km/h}$	$80 \text{ km/h} < v_{\max} \leq 160 \text{ km/h}$
Simplified proof of cross wind stability	Yes ^b	Yes, 5.3.2 + 5.4.2 or 5.3.3 + 5.4.2 or 5.3.3 + 5.4.3 or 5.3.4 + 5.4.2 <u>Restrictions:</u> 5.3.2 not applicable for trains with active tilting mode 5.4.2 not applicable for articulated trains	Yes, 5.3.4 + 5.4.2 <u>Restrictions:</u> 5.4.2 not applicable for articulated trains	Yes ^b	Yes, 5.3.2 + 5.4.2 or 5.3.3 + 5.4.2
Full proof of cross wind stability	No	Yes, 5.3.4 + 5.4.3 or 5.3.4 + 5.4.4	Yes, 5.3.4 + 5.4.3 or 5.3.4 + 5.4.4	No	Yes, 5.3.4 + 5.4.2 or 5.3.4 + 5.4.3
^a Above 360 km/h the methods shall be adapted taking account of compressibility effects.					
^b Regulated by national requirements (see Annex K for more information).					

Annex A indicates how these approaches are combined for practical cross wind stability analysis in various European countries.

5.3 Determination of aerodynamic coefficients

5.3.1 General

Various methods are available to determine the aerodynamic loading on passenger or freight vehicles. Static wind tunnel test data often serve as a part of the proof that the vehicle fulfils given specifications or requirements for rolling stock assessment. Data obtained from Computational Fluid Dynamics (CFD) simulations are often used for feasibility studies in the early vehicle design process. Data obtained with predictive formulae are usually used for a first analysis. The following subclauses describe how these methods shall be applied. Table 2 indicates their applicability for rolling stock assessment purposes.

5.3.2 Predictive formula

The predictive formula shall only be used subject to the following restrictions:

NOTE 1 The method is not valid for vehicles which differ much in their shape from the shape of current vehicles.

- The method is not valid for leading vehicles with a length L greater than 28 m or less than 10 m.
- The method is not valid if the vehicle(s) leading the investigated intermediate vehicle has an overall total length of less than 10 m.
- The method is valid only for rolling stock with a maximum semi-width of 1 700 mm.

NOTE 2 Rolling stock gauges e.g. G1, GA, GB, GC, DE3, GHE16, GEA16, GEB16, GEC16 and FIN1 according to EN 15273 (all parts) comply with the maximum semi-width of 1 700 mm.

The formula is deliberately conservative and therefore will overestimate the wind loading. The method predicts the wind load on a vehicle using the coefficient for the rolling moment around the lee rail. This is different from the rolling moment definition in 3.3, where the middle of the track is the moment reference centre. The rolling moment coefficient around the lee rail used here is estimated from the main physical dimensions of the vehicle.

The predictive formula allows the wind load to be calculated as follows:

$$c_{M_{x,lee}}(\beta) = \frac{(z_0 + z_1 \cdot \tilde{\beta} + z_2 \cdot \tilde{\beta}^2 + z_3 \cdot \tilde{\beta}^3) \cdot h_{VEH}^2 \cdot L_{VEH} \cdot f_L \cdot f_{VEH} \cdot z_4}{A_0 \cdot d_0} \quad (1)$$

with $\tilde{\beta} = \left| \arctan[z_5 \cdot \tan(\beta)] \right|$

where the parameters $z_0, z_1, z_2, z_3, z_4, z_5, f_L$, and f_{VEH} are given (see Table 3).

Table 3 — Parameter set for the standard ground configuration (standard gauge)

Parameter	Leading end car and locomotive	Mid-passenger vehicle	Freight vehicle
z_0	0		For $0^\circ \leq \beta \leq 40^\circ$: $z_0 = 0$ For $\beta > 40^\circ$: $z_0 = 0,55$
z_1	$4,3 \cdot 10^{-3}$ per degree		For $0^\circ \leq \beta \leq 40^\circ$: $z_1 = 0,013\ 75$ For $\beta > 40^\circ$: $z_1 = 0$
z_2	$2,2 \cdot 10^{-4}$ per degree to the power of two		0
z_3	$-2,1 \cdot 10^{-6}$ per degree		0
z_4	1,2		1
z_5	1,2		1
f_L	$f_L = 0,3 \cdot \frac{L_0}{L_{\text{VEH}}} + 0,75$ with $L_0 = 25\text{ m}$	1	1
f_{VEH}	1	0,75	1
A_0	10 m ²		
d_0	3 m		
NOTE	Factors z_1, z_2, z_3 are referring to angles in degrees.		

5.3.3 Simulations by Computational Fluid Dynamics (CFD)

5.3.3.1 General

The chief purpose of applying CFD is to determine the set of aerodynamic loads appropriate for determining the mechanical stability of a critical vehicle. The aerodynamic loads needed for such a study are usually the side and lift forces along with the moments of roll, pitch and yaw. In addition, CFD provides a prediction of the velocity and pressure fields, and easily allows different configurations to be taken into account.

The approach outlined here is similar to that recommended for reduced-scale wind tunnel measurements, see 5.3.4, in that a stationary train and a low turbulence block profile onset flow shall be used.

The flow around the vehicle is usually subjected to the following characteristics; three-dimensionality, high Reynolds' number, turbulence, deceleration and acceleration, curved boundaries, separation, possible reattachment, recirculation and swirling properties. The proper solution of this aerodynamic problem can only be determined by DNS (Direct Numerical Simulation) of the Navier-Stokes formulae which in practice is strongly limited by computational resources. Approximate solutions may be achieved by turbulence modelling through approaches such as: LES (Large Eddy Simulation), DES (Detached Eddy Simulation), RANS (Reynolds' Averaged Navier Stokes).

The flow around a vehicle is inherently unsteady, and varies with the geometry and yaw angle. However, RANS methods are sufficiently accurate for the purpose of these investigations. A commonly applied method to check the steadiness of the flow is to confirm that the residuals are reduced by three to four orders of magnitude and the loads of interest have converged with negligible cycling of the solution.

The chief challenge of CFD is the appropriate choice of an adequate combination of computational mesh, computational method and turbulence modelling. One advantage of CFD is that blockage effects can be minimized by using a sufficiently large domain size without compromising the Reynolds' number or Mach number.

5.3.3.2 Benchmark tests

In order to demonstrate the appropriateness of the CFD approach, calculations shall be made for at least one specified benchmark vehicle (see 5.3.4.2 and Annex C), in a similar fashion to that described for validating wind tunnel measurements in 5.3.4.2. The results from these calculations shall be compared to the benchmark values derived from wind tunnel measurements. The quality criteria defined in 5.3.4.2 shall be applied.

5.3.3.3 Vehicle model

The representation of the test vehicle and adjacent vehicles models, as far as intercar-gaps, vehicles length and modelling accuracy are concerned, shall be according to that for wind tunnel measurements, see 5.3.4.8 and 5.3.4.9.

Contact between the wheels and rail or ground may be simplified, e.g. by cutting the base of the wheel to avoid numerical singularities in the contact point.

5.3.3.4 Computational domain

The model dimensions may either be at full scale or model scale. The latter may be advantageous from a practical viewpoint if results are compared with wind tunnel measurements at some point.

The domain boundaries shall not interfere with the flow around the vehicle in a physically incorrect way.

The requirements for blockage ratio shall be taken from 5.3.4.7.

The computational domain shall extend in the streamwise direction relative to the vehicle of interest: at least 8 characteristic heights upstream and 16 characteristic heights downstream. The characteristic height is defined by the distance between the top of the train and the ground, e.g. when modelling an embankment this height is the height of the embankment including ballast and rail plus the height of the train.

5.3.3.5 Computational mesh

The mesh shall meet basic requirements concerning cell sizes adjacent to no-slip walls, appropriate for the selected computational method and turbulence model. Typical values for the dimensionless wall distance y^+ for the first cell layer for RANS simulations are of the order of 1 for low-Reynolds' number turbulence models and typically 30-150 for high-Reynolds' number turbulence models.

The mesh should capture regions of high pressure/velocity gradient such as: boundary layers, vortices, stagnation zones, recirculation cells, wakes, flow acceleration.

The design of mesh for different yaw angle calculations should be kept as fixed as possible, in terms of the size and distribution of computational cells. The location and size of regions of relatively high resolution may have to be varied. A sufficient number of mesh nodes between the vehicle and boundaries shall be used.

Mesh independency for the vehicle under investigation shall be proven by changing the mesh resolution at least in regions of high gradients with two levels of mesh refinement as a minimum. The mesh resolution shall be different by a factor of 1,5 in each spatial direction in the regions where strong velocity gradients have been found. The results of the three meshes shall show good agreement in both flow topology and force coefficients. The rolling moment coefficient around the lee rail shall have an accuracy of 3 % between the three refinements for yaw angles between 10° and 50°. The largest of the obtained values at each yaw angle shall be taken as the result.

5.3.3.6 Computational method

The computational method shall be able to model the viscous, turbulent, unsteady, three-dimensional and strongly separated flows. However, steady methods may be used if the steadiness of the flow is evident.

The majority of the methods are based on continuum theory governed by the momentum formulae (Navier-Stokes formulae), but methods based on kinetic gas theory (Lattice-Boltzmann formulae) may be used as well.

5.3.3.7 Turbulence modelling

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

Calculations shall involve a sensitivity test, using the most appropriate turbulence models. If ambiguous results are obtained, wind tunnel measurements shall be used instead.

Commonly used turbulence models are the $k-\epsilon$ and $k-\omega$ models. However, these models are known to produce excessive eddy viscosity which could lead to underestimation of recirculation regions and suppression of flow separation. Therefore, such models should be used with care.

Alternative approaches exist that may require more computational effort and are part of ongoing research activities.

5.3.3.8 Boundary conditions

The onset wind profile just upstream of the vehicle of interest shall have a uniform, i.e. block profile, to agree with the specifications in 5.3.4.4 for wind tunnel measurements.

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 may be either stationary or moving with a relative velocity corresponding to the vehicle speed.

The top and lateral plane boundary conditions shall be appropriate for the train and yaw angle configuration under investigation.

5.3.3.9 Reynolds' number

The Reynolds' number " Re " is based on the flow speed at the onset boundary and calculated with a characteristic length of 3 m (at full scale) and shall be no lower than that specified for the wind tunnel measurements in 5.3.4.5.

5.3.3.10 Test programme requirement

See 5.3.4.11 and 5.3.4.12.

5.3.3.11 Data interpolation

See 5.3.4.13.

5.3.3.12 Documentation

Conformity with all requirements defined in 5.3.3 shall be documented.

5.3.4 Reduced-scale wind tunnel measurements

5.3.4.1 General

The purpose of the wind tunnel tests is to enable the determination of the vehicle aerodynamic force and moment coefficients, including the rolling moment coefficient around the lee rail. This specific coefficient is a non-dimensional form of the full-scale wind induced moment acting around the line of contact between the wheels and the lee rail. It is mainly this moment that unloads upwind wheels in strong winds and, at the limit, could cause a vehicle to overturn.

The type of wind tunnel test that is described here uses static models of the train in a uniform, low turbulence onset flow.

A block profile and low turbulence intensity are usually not present in full scale; nevertheless this is required in the wind tunnel, because it allows a more reliable and repeatable test than more complex flow simulations. A simple block profile, except for the thin boundary layer on the floor, ensures more repeatable conditions between different wind tunnels.

NOTE 1 Various boundary layer techniques are available in wind tunnels, e.g. a moving belt, boundary layer suction, wall jet blowing or a splitter plate have proven successful.

This type of wind tunnel test is effectively a simplification of more complex tests that use moving models to simulate the movement of the train over the ground with an atmospheric boundary layer. These more complex tests require further research before they can be considered standard. Requirements for wind tunnel testing with a static model in an atmospheric boundary layer are described in Annex G.

NOTE 2 Moving ground simulation meeting the requirements of 5.3.4.11 is technically difficult to achieve.

It is permissible to use different types of wind tunnels. Details of the wind tunnel used shall be described according to EN 14067-4.

5.3.4.2 Benchmark test

Wind tunnel tests which are used within the assessment process of rolling stock shall include test results of specified benchmark vehicles. For other wind tunnel tests it is recommended to include tests of specified benchmark vehicles. If wind tunnel benchmark tests are carried out, at least one of the three benchmark vehicle models for ICE 3 leading vehicles, TGV Duplex power car or ETR 500 power car (see Annex C) shall be used.

Results of wind tunnel benchmark tests shall be available for basically the same set-up as for the vehicle under investigation. The tests for the new vehicle should be conducted using the same techniques, configurations, onset wind conditions, equipment as the benchmark tests. These benchmark tests shall be repeated if there is any change in the wind tunnel set-up (e.g. in wind tunnel, Reynolds' number, ground configuration, ground models, balance, boundary layer properties).

The measured test results for the benchmark vehicle $c_{Mx,lee,test}$ shall be compared with the reference values for that benchmark vehicle $c_{Mx,lee,bmk}$ (see Annex C) to determine whether the wind tunnel tests are giving results which are within the required tolerances. Exact agreement is not expected due to differences between different wind tunnels and experimental set-ups. The required tolerances for low turbulence tests are:

$$\max \left(\left| \frac{c_{Mx,lee,test} - c_{Mx,lee,bmk}}{c_{Mx,lee,bmk}} \right| \right) < \varepsilon_{\max} \quad (2)$$

$$\text{mean} \left(\left| \frac{c_{Mx \text{ lee, test}} - c_{Mx \text{ lee, bmk}}}{c_{Mx \text{ lee, bmk}}} \right| \right) < \varepsilon_{\text{mean}} \quad (3)$$

Good target tolerance values have been found to be $\varepsilon_{\text{max}} = 0,15$ and $\varepsilon_{\text{mean}} = 0,1$ for the yaw angles relevant for the CWC calculation.

Where the results fall within these tolerances, the test technique is deemed to be an acceptable basis for deriving the required results. If however, any of these tolerances are not achieved, modifications shall be made to the test arrangements to achieve the target tolerances.

5.3.4.3 Turbulence level

The atmospheric turbulence layer shall not be represented in the wind tunnel tests. It is necessary to ensure that the turbulence level $Tu_x \leq 0,025$, where:

$$Tu_x = \left(\overline{u'^2} / \overline{u}^2 \right)^{0,5} \quad (4)$$

with u denoting the streamwise velocity component.

5.3.4.4 Boundary layer

The wind tunnel velocity profile shall have a uniform, i.e. block, profile. The flow speed shall be independent of the height above ground, except for a thin boundary layer on the wind tunnel floor. The thickness of the boundary layer, $\delta_{99\%}$, at the axis of rotation of the turntable shall be less than 30 % of the vehicle height. The boundary layer thickness and velocity profile shall be determined without a train and without the ground model present.

5.3.4.5 Reynolds' number

The Reynolds' number, Re based on the wind tunnel speed and on the characteristic length of 3 m (divided by the model scale) shall be greater than $2,5 \times 10^5$ to ensure flow similarity between model and full-scale flows. A check shall be made that the results are nearly Reynolds' number independent. As a minimum the results for $c_{Mx \text{ lee}}$ for at least one configuration for each vehicle tested shall be documented over the range $[0,6 Re_{\text{max}}, Re_{\text{max}}]$.

5.3.4.6 Mach number

In general, the Mach number shall be no higher than 0,3. However, if the real train operates at Mach numbers higher than 0,3, the test Mach number shall not be higher than the Mach number of the real train.

5.3.4.7 Blockage

The blockage ratio x_B is defined at a yaw angle of 30° . It is calculated as the ratio of the projected side area of the total modelled configuration (train model + embankment, if present) to the wind tunnel cross-sectional area. The blockage ratio x_B shall be less than 15 %.

For open and partially open test sections (e.g. three quarter open or slotted walls) no blockage correction is needed for blockage ratios smaller than 5 %. For x_B between 5 % and 15 % the blockage corrections described in Annex B may be used. In closed test sections, the coefficients are overestimated, therefore it is conservative not to apply a correction here.

5.3.4.8 Train model setup

All linear dimensions of the model vehicle and ground model shall be scaled in the same ratio as the model scale so that geometric similarity is achieved.

The ratio of the total length of the train model to the width of the tunnel should not be so large that the presence of the side walls of the tunnel causes any distortions to the flow around the ends of any leading vehicles and should be less than 0,75.

When conducting wind tunnel tests it is essential to cover the realistic worst case train composition.

For all passenger vehicles and locomotives under investigation at least half a down-stream vehicle shall be placed next to the tested model. It is recommended to use a down-stream model of full vehicle length to be placed next to the tested model. If the vehicle under investigation is not a leading vehicle, at least one full vehicle ahead needs to be present to ensure realistic upstream flow conditions. The upstream and downstream model should be of similar cross-section to the tested model.

Freight wagons which can possibly run behind an empty flat wagon shall be tested using an empty standard two-axle container trailer model as upstream body. For freight wagons no downstream body shall be used.

The intercar-gap between the vehicles shall be represented with the correct separation between adjacent vehicles. Mechanical contact between the tested model and the passive bodies shall be excluded at all times. Vibration of the tested model or adjacent passive models shall be minimized.

5.3.4.9 Modelling accuracy

The live vehicle shall be modelled sufficiently accurately that modelling simplifications do not result in unrealistic flows. Experience shows that relatively minor modelling simplifications have the potential to change the position of flow separation and hence to cause substantial changes in the aerodynamic rolling moment.

The underlying shape of the vehicle body shall be modelled to a tolerance of $-0,5\%$ and $+1\%$ of a given dimension of the body shape. Smooth curved surfaces shall be modelled as such, rather than as polygonal approximations, so as to avoid artificial flow separations. Aerodynamically significant features on the train side and roof shall be modelled. The surface of the model shall be generally smooth, but where there are localized regions of surface roughness on the vehicle these should be simulated. It is less important to model the underbody of the train in fine detail, however, the general shape of the underbody and the bogie regions and the distribution of blockage shall be represented. The wheels shall be flattened to prevent contact with the ground. The pantograph should not in general be modelled. If the pantograph is included, special care shall be taken to exclude local Reynolds' number effects at the pantograph. The accuracy of the modelling of the dummy vehicles is not as critical as the live vehicle, but the general principles for the live vehicle should be followed.

The model should be symmetrized in y-direction, even if the full scale vehicle has slight asymmetries e.g. in the underfloor region or on the roof. The advantage is the chance to judge the quality of the wind tunnel by comparing the left side and right side coefficients, which is very valuable information for the error analysis. To verify the symmetry of the incident flow, check measurements shall be performed with both positive and negative yaw angles.

5.3.4.10 Instrumentation requirements

The required moment and force coefficients shall be derived from measured values of wind speed, moments and forces, and calculated air density. These measured values require anemometers, a force balance, a temperature sensor and a pressure sensor.

— Speed measurement:

The wind speed shall be measured upstream of the model where the wind speed includes boundary layer treatment effects but is not affected by the vehicle model and its environment. Application of blockage corrections may be considered (see 5.3.4.7)

Dynamic pressure measurement devices shall have an accuracy of better than 2 % and the resolution shall be better than 1 %. Air speed measurement devices shall have an accuracy of half the above values.

— Force and moment balance:

The mean forces and moments shall be measured using a force and moment balance. The rolling moment around the lee rail should have an accuracy of 5 % at the lowest yaw angle needed for calculation of the CWC.

The model shall be designed so that oscillation of the model mounting system will not affect the analysis. If this is not achieved, modifications to the model and mounting shall be undertaken. Demonstration of the system dynamic response shall be provided in the test documentation.

— Calculation of air density:

The air density ρ shall be calculated from the average measured temperature, and pressure for each (data acquisition) test using the ideal gas law with a specific gas constant of 287 J/(kg·K).

5.3.4.11 Standard ground configuration single track ballast and rail

A properly scaled simulation of the standard ballast profile and rails shall be provided (see reference configuration in Figure 2 and Figure 3), to the following level of detail: the underlying shape shall be modelled to ± 5 cm full scale and features with full-scale dimensions greater than 10 cm shall be modelled. Any smaller features shall be modelled as generalized surface roughness. Notwithstanding the above, individual ballast stones should not be modelled.

Particular care shall be taken with the height of the vehicle relative to the rails so that this is accurate to ± 5 cm full scale. The height shall vary by no more than $\pm 2,5$ cm full scale when the vehicle is removed and then replaced during the tests. The distance from the upstream end of the ground model to the leading end of the train model (or upstream body) shall be at least 8 m (in full-scale dimensions). The reference configuration shall be applied unchanged to any track gauge in the scope of the standard.

NOTE As the train is set symmetrically on the single-track ballast and rail configuration, for rolling stock with track gauge other than 1 435 mm, the wheel sets will not be in line with the rails.

Dimensions in millimetres

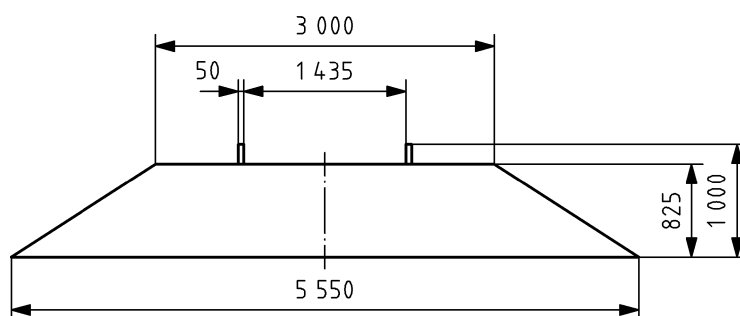


Figure 2 — Sketch of the wind tunnel configuration single track ballast (front view, 1:1 scale)

Dimensions in millimetres

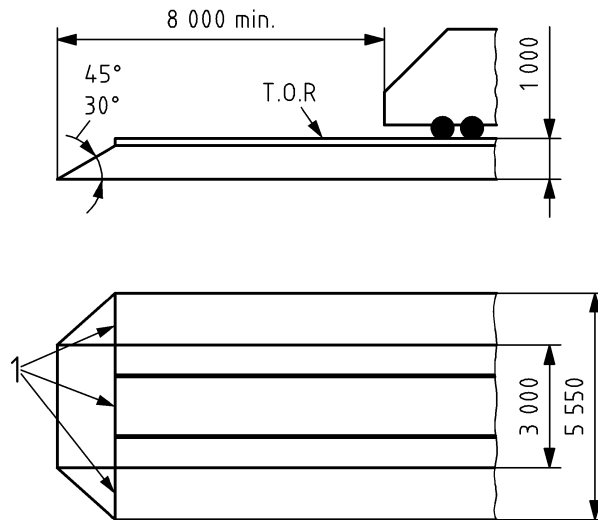
**Key**1 edge rounding $R = 300$

**Figure 3 — Sketch of the wind tunnel configuration single track ballast
(side and top view, 1:1 scale)**

5.3.4.12 Test program requirements

The effect of strong wind on rail vehicles varies not only with train design, but also whether the train is on flat ground or embankments, whether the train is canted or tilted, as well as with the angle of the wind to the track. It is not possible to test for all these variables and so tests are reduced to the following standard test programme:

- The ground configuration shall be according to 5.3.4.11.
- The measurements relevant for the CWC calculation shall be made with yaw angles in 5° steps up to $\beta = 50^\circ$, followed by 10° steps up to the maximum yaw angle. Additionally, where practical, measurements should also be made at $\beta = 90^\circ$.
- For vehicles without an active tilting system, the aerodynamic coefficients shall be measured for the vehicle at a tilting angle of 0° (no tilting). For vehicles with an active tilting system, the aerodynamic coefficients shall be measured for the vehicle at a tilting angle of 0° , at the maximum tilting angle and the minimum tilting angle.

For high speed trains with $v_{\max} \geq 250$ km/h, interoperability requirements are set out in 5.6.1¹.

NOTE An overview of test requirements for other approaches is given in Annex A.

5.3.4.13 Data interpolation

The discrete values of mean force and moment coefficients shall be interpolated to obtain continuous representations of these coefficients. The interpolation method shall be documented.

¹ See also TSI HS/RST 2008.

5.3.4.14 Documentation

Conformity with all requirements defined in 5.3.4 shall be documented.

5.4 Determination of wheel unloading due to cross winds

5.4.1 General

Various methods are available to determine the wheel unloading on passenger or freight vehicles due to cross wind. Time-dependent multi-body simulation and an advanced quasi-static approach often serve as a part of the proof that the vehicle fulfils given specifications or requirements for rolling stock assessment. Data obtained from a simple method (quasi-static three mass model) are considered to be less precise but conservative because of built-in margins.

5.4.2 Simple method

5.4.2.1 Application range and restrictions

The simple assessment method is subject to the following restrictions:

- The method is suitable only for vehicles with two sets of running gear or two single axles. Articulated trains, vehicles with Jacobs bogies or similar solutions with transmission of roll moments between car bodies shall not be evaluated with this method.
- The method may be used for tilting trains, but the effects of tilt shall be included in the mass distribution, the suspension characteristics and the body centre of gravity movements due to the added effect of tilt.

5.4.2.2 General approach

For the calculation of the characteristic wind speed the moment of equilibrium around the lee rail is calculated. The procedure relies on four fundamental quantities:

- the restoring moment M_m due to the vehicle masses;
- the moment M_{la} due to the uncompensated lateral acceleration;
- the moment M_{CoG} due to the lateral movement of the centre of gravity of suspended masses (due to sway and lateral displacement);
- the aerodynamic moment $M_{x,lee}$ due to the wind load.

The vehicle is considered to consist of three principal masses: the unsprung mass m_0 , the primary sprung mass m_1 and the secondary sprung mass m_2 .

5.4.2.3 Computation of the characteristic wind speed

Using the coordinate system defined in 3.3 with the exception of the wind from the right in the direction of travel (see Figure 4) the moment of equilibrium around the lee (left) rail is given by:

$$\Sigma M = f_{AQ} \cdot \frac{1}{f_m} \cdot M_m + M_{CoG} + M_{la} - M_{x,lee} = 0 \quad (5)$$

The factor f_{AQ} describes the relative wheel unloading and is fixed to 0,9. The factor f_m is a method factor which considers uncertainties in the method. It shall be chosen according to Table 4.

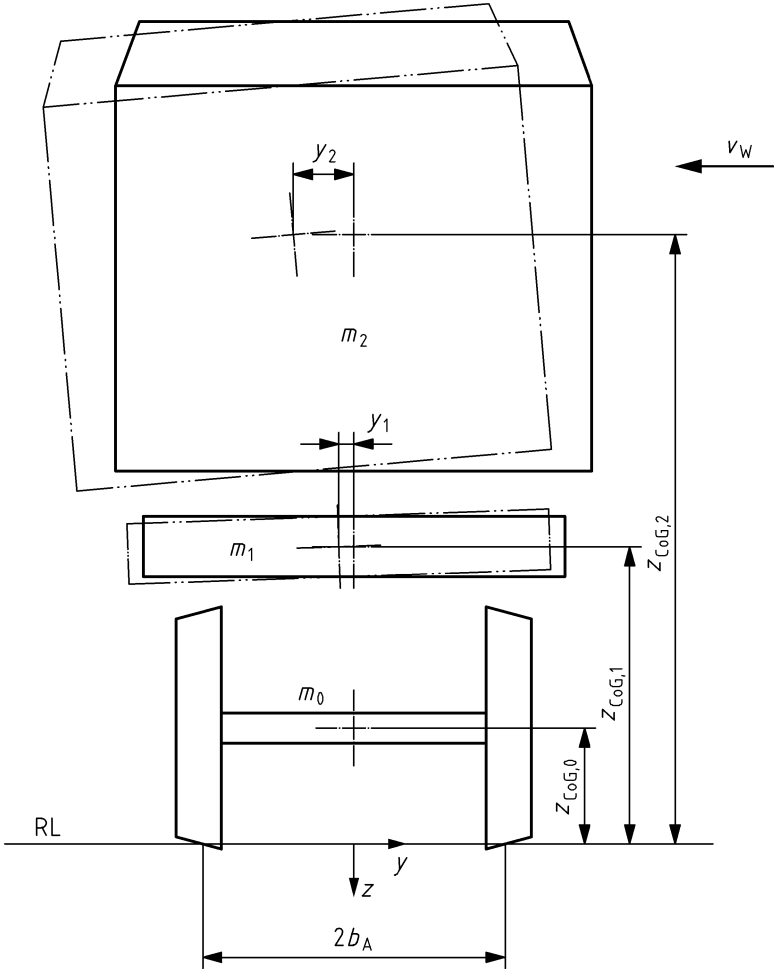


Figure 4 — Illustration of three mass model

Table 4 — Method factor f_m for various vehicle types

	Passenger vehicles	Freight wagons	Locomotives
Method factor f_m	1,20	1,15	1,20

The moments in Formula (5) are calculated according to Formulae (6) to (11).

$$M_m = m \cdot g \cdot b_A \tag{6}$$

$$M_{CoG} = (m_1 \cdot y_1 + m_2 \cdot y_2) \cdot g \tag{7}$$

$$M_{la} = m \cdot a_q \cdot z_{CoG} \tag{8}$$

with

- negative values for y_1 or y_2 for movements of the CoG to the left;
- negative values for z_{CoG} ;

- unsprung masses m_0 ;
- primary suspended masses m_1 ;
- secondary suspended masses m_2 ;
- the total vehicle mass $m = m_0 + m_1 + m_2$;
- the lateral contact spacing:
 - for 1 435 mm nominal gauge is $2b_A = 1,5$ m;
 - for 1 520 mm nominal gauge is $2b_A = 1,58$ m;
 - for 1 524 mm nominal gauge is $2b_A = 1,585$ m;
 - for 1 668 mm nominal gauge is $2b_A = 1,733$ m;
 - for 1 600 mm nominal gauge, a proper value of $2b_A$ shall be determined.
- the uncompensated lateral acceleration a_q ; for a particular curve of radius R_c [m] with cant H_{cant} [m];

$$a_q = \frac{v_{\text{tr}}^2}{R_c} - \frac{gH_{\text{cant}}}{2b_A}$$

(R_c positive for curve to the right, positive value for h results in rotation of track around the x-axis);

- the height of the centre of gravity of the unsprung masses $z_{\text{CoG},0}$ (usually the wheel radius);
- the height of the centre of gravity of the primary sprung masses $z_{\text{CoG},1}$;
- the height of the centre of gravity of the secondary suspended masses $z_{\text{CoG},2}$;
- the height of the centre of gravity of the total vehicle $z_{\text{CoG}} = \left(\frac{m_0 \cdot z_{\text{CoG},0} + m_1 \cdot z_{\text{CoG},1} + m_2 \cdot z_{\text{CoG},2}}{m} \right)$.

The aerodynamic moment induced by the wind is:

$$M_{x,\text{lee}} = \frac{1}{2} \cdot \rho_0 \cdot v_a^2 \cdot A_0 \cdot d_0 \cdot c_{Mx,\text{lee}}(\beta) \quad (9)$$

The lee rail rolling moment coefficient $c_{Mx,\text{lee}}(\beta)$ shall be determined from wind tunnel tests, from CFD simulations or from calculations using predictive formulae (see 5.3).

The relative wind speed and the yaw angle β shall be calculated as follows:

$$v_a^2 = \left(v_W \cdot \cos \beta_W + v_{\text{tr}} \right)^2 + v_W^2 \cdot \sin^2 \beta_W \quad (10)$$

$$\beta = \arctan \left(\frac{v_W \cdot \sin \beta_W}{v_{tr} + v_W \cdot \cos \beta_W} \right) \quad (11)$$

Formulae (5) to (11) shall be solved to obtain values for the characteristic wind speed v_W (v_{tr} , a_q , β_W). This will require iterative methods.

5.4.3 Advanced quasi-static method

5.4.3.1 General

This clause describes a quasi-static method which considers kinematics of the main bodies of a vehicle. Dynamic effects, e.g. from dampers, are excluded. It has been shown that this method leads to characteristic wind speeds no higher than the method utilizing time-dependent multi-body simulation (MBS) presented in 5.4.4. This method is therefore conservative.

The underlying principle is to divide the vehicle into the relevant concentrated masses which are connected with coupling elements. The mechanical system results in a set of formulae which may be determined using MBS codes or by explicit formulation of the formulae.

5.4.3.2 Computational method

In this method, a quasi-static approach is used for the calculation of characteristic wind curves (CWCs) with the main effects and influencing factors on the vehicles' side wind stability being considered.

The following input parameters (bracketed) are required:

- unsprung masses, such as wheel sets (masses, positions of the centres of gravity);
- primary suspended masses, such as bogies, mounted parts (masses, positions of the centres of gravity);
- secondary suspended masses such as car body, tilting technology (masses, positions of the centres of gravity);
- primary and secondary suspension elements (linear or nonlinear stiffnesses, positions);
- anti-roll bars (rotational stiffnesses);
- primary and secondary stops in the lateral and vertical directions (position and characteristics);
- wind loads (aerodynamic coefficients);
- influence of tilting technology and/or active transverse centring;
- forces between adjacent vehicles due to coupling elements.

A model of the system is used for deriving the mathematical formulation which is used for the calculation of the characteristic wind curves (CWCs). A simple model (five mass model) is suitable for many vehicles. A simplified vehicle-specific MBS model may be set up for those vehicles for which the simple model is not adequate. Verification shall be carried out for each vehicle model.

The decision on the appropriateness of a five mass model depends on the structure of the vehicle and on the coupling elements to adjacent vehicles. The five mass model described below is suitable for the CWC calculation for vehicles with the following characteristics:

- vehicle with two sets of running gear;

- no coupling elements to adjacent vehicles or running gear, where major static lateral and vertical forces as well as rolling moments are transferred;
- vehicles with active transverse centring or tilting technology. The influence of the active components on the displacement of the centre of gravity shall be included, with the following aspects being considered:
 - If the active components effect a displacement of the car body's centre of gravity towards the interior of the curve, the displacement of the centre of gravity may be considered and included.
 - If the active components effect a displacement of the car body's centre of gravity towards the exterior of the curve, the displacement of the centre of gravity shall be considered and included.

An example derivation of the mathematical system of formulae of a simple five mass model is given in Annex H. The subsequent CWC calculation may be carried out by using suitable software packages.

5.4.3.3 Vehicle model verification

A verification of the vehicle model used should prove that the main vehicle characteristics affecting the side wind stability are represented with sufficient accuracy. The verification of the vehicle model shall be carried out by comparison of the calculation with measured results based on the following values:

- The sums of the axle loads of each bogie shall be compared with the measurements (from e.g. by weighing). The deviation from the measurements shall not exceed $\pm 1\%$. If there are several values measured, the mean value should be used.
- The maximum bump stop distance shall be modelled according to the nominal design data.
- The model flexibility coefficient (suspension coefficient) should be compared with that from full-scale tests. The definition of the flexibility coefficient, (suspension coefficient) s , shall comply with the definition used for kinematic gauge calculations. If more than one value for s is available from the test, the average should be taken. If better model verification methods are available (e.g. static or dynamic measurements of the Q -forces), these may be used instead. The results of the simulation shall lie within the tolerances of the measured values.
- If the verification of the vehicle model calculations are unsatisfactory, the MBS model shall be modified. Modifications of the MBS model shall be verified according to the above.

5.4.3.4 Calculation of the CWC

For the CWC calculation, the equilibrium position of the vehicle shall be determined depending on the external forces acting on the vehicle. The following forces and moments shall be considered:

- mass forces due to the acceleration due to gravity (g) and the uncompensated lateral acceleration (a_q);
- spring forces and bump stop forces due to the suspension and due to anti-roll bars;
- wind forces acting on the car body using the full set of aerodynamic coefficients, but neglecting the drag coefficient c_{Fx} .

The stiffness of metallic bump stops should be considered. A recommended minimum value for the stiffness of the metallic bump stop between the car body and bogie is 10^8 N/m.

Depending on the vehicle and wind speed, the following define the wind forces and moments:

$$F_i = \frac{1}{2} \cdot A_0 \cdot \rho \cdot v_a^2 \cdot c_{Fi}(\beta) \quad (12)$$

$$M_i = \frac{1}{2} \cdot d_0 \cdot A_0 \cdot \rho \cdot v_a^2 \cdot c_{Mi}(\beta), i = x, y, z \quad (13)$$

The relative flow velocity and the yaw angle are calculated as follows (see also 3.3):

$$v_a^2 = (v_{tr} + v_W \cos \beta_W)^2 + (v_W \sin \beta_W)^2 \quad (14)$$

$$\beta = \arctan \left(\frac{v_W \cdot \sin(\beta_W)}{v_{tr} + v_W \cdot \cos(\beta_W)} \right) \quad (15)$$

When calculating the wheel-rail forces (Q -forces), the displacement of the contact point in the wheel flange direction shall be considered (see Figure 5).

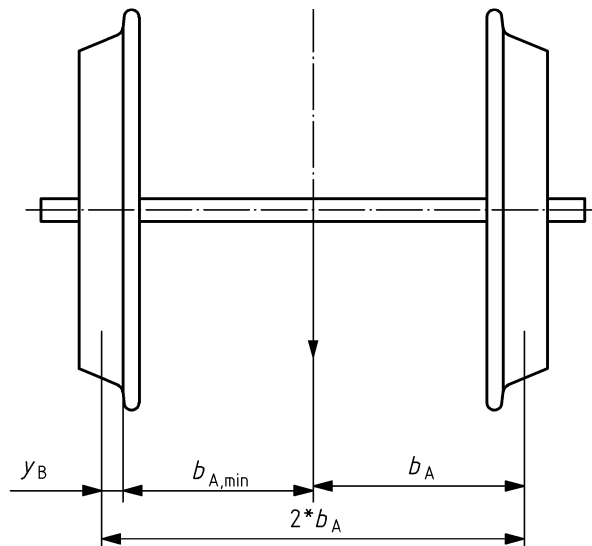


Figure 5 — Illustration of contact point

The value $b_{A,min}$ is the minimum width between the contact points, and:

$$2b_A = 1,5 \text{ m (for nominal track gauge 1 435 mm, for other track gauges see 5.4.2.3.)} \quad (16)$$

and the maximum displacement of the contact point on the wheel in the wheel flange direction is:

$$y_B = 0,028 \text{ m} \quad (17)$$

for nominal track gauge 1 435 mm, for the other gauges use the corresponding value.

$$\text{With } b_{A,min} = b_A - y_B \quad (18)$$

For the calculation of the characteristic wind curves, the equilibrium position is to be calculated for different wind speeds. The definition of the characteristic wind speed is that wind speed which leads to a residual load of 10 % of Q_0 for any wheel for a two axle vehicle or averaged over the wheel sets of a bogie for a bogied vehicle.

5.4.3.5 Verification

The implementation shall be proven by a verification.

If the typical five mass model is used, each CWC calculation for a vehicle shall include the CWC calculations for the two example vehicles specified in Annex H. The process is proved when the calculated CWC of the vehicles at $\beta_w = 90^\circ$ deviate by a maximum of $\pm 0,5$ m/s from the CWC of the example vehicles.

5.4.4 Time-dependent MBS method using a Chinese hat wind scenario

5.4.4.1 General

An MBS program shall be used along with a gust scenario. Modelling shall consider the most critical vehicle of the train and that this vehicle is empty (i.e. with operational mass in working order according to EN 15663 but without wear allowances). A check shall be made that an even distribution of passengers is not more critical than an empty vehicle (for instance due to centre of gravity movements), e.g. by using a simplified check with a fully static approach.

If there is no roll restraint at the coupling, only the critical vehicle needs to be modelled, otherwise adjacent vehicles shall also be modelled.

Track irregularities shall not be considered.

For the assessment of interoperable rolling stock on standard gauge 1 435 mm, the calculation shall be carried out with standard gauge, rail profile 60E2, new wheel profile and 1/20 and 1/40 rail inclinations. The worst case shall be used for assessment against the limits. The calculation shall be performed for standard gauge and standard rail profiles incl. rail inclination using new wheel profiles.

The criterion that defines the CWC is the average value of wheel unloading, ΔQ , of the most critical running gear (bogie or single axle in case of single axle running gear). This unloading shall not exceed 90 % of the average static wheel loads, Q_0 , of the running gear as given in the following formula:

$$\frac{\Delta Q}{Q_0} < 0,9. \quad (19)$$

The CWCs obtained are referenced to the peak wind of the time-dependent gust.

5.4.4.2 Chinese hat gust scenario

This subclause gives a short description of the gust model. The formulae given here refer to a wind direction normal to the track. The full mathematical description for this gust model for all wind directions is given in Annex I.

The gust generated for the method has a fixed amplitude, (corresponding to a probability level of amplitude approximately 99 %) and a probability level of exceedance of 50 % for the gust duration (the mode of the distribution). Furthermore, the chosen approach has the following characteristics:

- The gust time-space model (bi-exponential) corresponds to an approximation of the average of a random process in the vicinity of a local maximum (see Figure 6).
- The mean wind is assumed to be horizontal; only the along wind component U_{mean} is used. This component represents the prominent part of wind fluctuations and is the projection of the instantaneous wind vector in the mean wind direction.
- Variations of wind direction in the period of the gust are not taken into account.

- Temporal variations are neglected in favour of spatial variations, i.e. the gust is not convected with the mean wind speed.

The input data for the scenario are:

v_{tr} train speed,

U_{max} maximum gust wind speed,

β_w wind direction with respect to the line.

The following parameters are fixed:

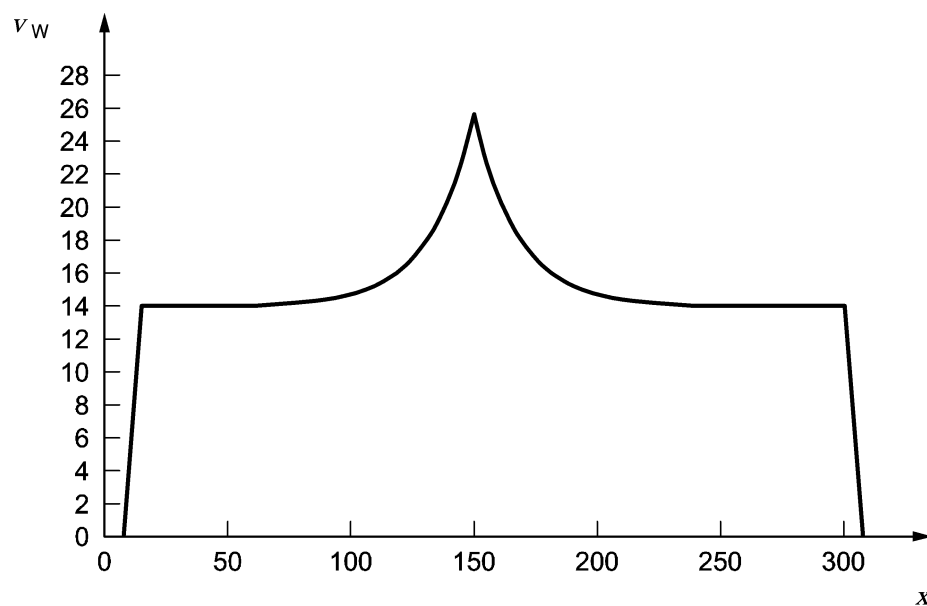
$h_z = 4$ m reference height,

$\tilde{A} = 2,84$ normalized gust amplitude $\tilde{A} = (U_{max} - U_{mean}) / \sigma_u$ with mean wind speed U_{mean} ,

$h_{z0} = 0,07$ m roughness height of sites representative of interoperable lines,

$Pr(T) = 0,5$ probability of a gust of duration T for a given amplitude.

For the calculation of the characteristic wind curves (CWCs), the spatial distribution of the wind is described with a mathematical model, with the shape plotted in Figure 6.



Key

x space, in metres

v_w wind speed, in metres/second

Figure 6 — Example of the spatial distribution of the wind using a Chinese hat gust model

The wind gust is fixed in space. It is assumed that the train velocity is constant, thus the temporal distribution can be evaluated from the spatial one by transformation.

The mean wind speed is calculated from the maximum wind speed:

$$U_{\text{mean}} = \frac{U_{\text{max}}}{1,694\ 6} \quad (20)$$

The power spectral density is calculated from:

$$S_u(n) = \frac{22,983\ 9\ \text{m} \cdot U_{\text{mean}}}{\left(1 + 652\ 107\ \text{m}^2 \cdot \left(\frac{n}{U_{\text{mean}}}\right)^2\right)^{\frac{5}{6}}} \quad (21)$$

where the frequency range is limited to $n = [1/300\ \text{Hz}, 1\ \text{Hz}]$.

The characteristic frequency f_{gust} of the gust is the integral:

$$f_{\text{gust}} = 0,239\ 091 \times \left[\frac{\int_{1/300}^1 n^2 \times S_u(n) dn}{\int_{1/300}^1 S_u(n) dn} \right]^{0,5} \quad (22)$$

which can be solved numerically e.g. by performing a trapezoidal numerical integration using a resolution of at least $\Delta n = 1/300\ \text{Hz}$.

The wind speed normal to the vehicle along the track is calculated from:

$$v_{W-90} = U_{\text{mean}} \cdot (1 + 0,694\ 6 \cdot C_{90}) \quad (23)$$

$$\text{where } C_{90} = e^{\frac{-16 \cdot f_{\text{gust}} \cdot \tilde{x}}{U_{\text{mean}}}} \quad (24)$$

and $\tilde{x}$ represents the spatial distance towards the position of the maximum amplitude of the gust.

The mathematical description only refers to the second half of the Chinese hat where the wind decays from U_{max} to U_{mean} . Since the exponential decay does not reach the level of the mean wind speed U_{mean} at any instant, the Chinese hat shall be confined to an appropriate region (see Figure 7):