

Railway applications — Aerodynamics

Part 6: Requirements and test procedures for cross wind assessment

ICS 45.060.01

National foreword

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Contents

Page

Foreword.....	7
Introduction	8
1 Scope	9
2 Normative references	9
3 Terms and definitions	9
4 Symbols and abbreviations	9
5 Methods to assess cross wind stability of vehicles	13
5.1 General.....	13
5.2 Applicability of cross wind methodologies for rolling stock assessment purposes	13
5.3 Determination of aerodynamic coefficients	14
5.3.1 General.....	14
5.3.2 Predictive equations.....	14
5.3.3 Simulations by Computational Fluid Dynamics (CFD)	16
5.3.4 Reduced-scale wind tunnel measurements	18
5.4 Determination of wheel unloading	23
5.4.1 General.....	23
5.4.2 Simple method using a two-dimensional vehicle model (three mass model).....	23
5.4.3 Advanced quasi-static method.....	26
5.4.4 Time-dependent MBS method using a Chinese hat wind scenario.....	29
5.5 Presentation form of characteristic wind curves (CWC)	37
5.5.1 General.....	37
5.5.2 CWC presentation form for passenger vehicles and locomotives.....	37
5.5.3 CWC presentation form for freight wagons	39
6 Method to acquire the needed railway line data.....	40
6.1 General.....	40
6.2 Presentation form of railway line data.....	40
6.2.1 General.....	40
6.2.2 Plan profile	40
6.2.3 Vertical profile	41
6.2.4 Track design speed	42
6.2.5 Walls.....	43
6.2.6 Meteorological input data for line description.....	43
6.2.7 Integrated line database.....	44
6.2.8 Required minimum resolution/accuracy	46
7 Methods to assess the wind exposure of a railway line	46
8 Methods to analyse and assess the cross wind risk	46
9 Required documentation	47
9.1 General.....	47
9.2 Assessment of cross wind stability of passenger vehicles and locomotives	47
9.3 Assessment of cross wind stability of freight vehicles.....	47
9.4 Acquisition of railway line data	48
Annex A (informative) Application of methods to assess cross wind stability of vehicles within Europe.....	49
Annex B (informative) Blockage correction	53
Annex C (normative) Wind tunnel benchmark test data for standard ground configuration	55

Annex D (informative) Other ground configurations for wind tunnel testing	59
Annex E (informative) Wind tunnel benchmark test data for other ground configurations	63
Annex F (informative) Embankment overspeed effect	76
Annex G (informative) Atmospheric boundary layer wind tunnel testing	77
Annex H (informative) Five mass model	83
Annex I (normative) Mathematical model for the Chinese hat	98
Annex J (informative) Stochastic wind model	105
Annex K (informative) Stability of passenger vehicles and locomotives against overturning at standstill according to national guidelines	113
Annex L (informative) Information on methods to assess the wind exposure of a railway line	116
Annex M (informative) Migration rule for this European Standard	119
Annex ZA (informative) Relationship between this European Standard and the Essential Requirements of EU Directive 2008/57/EC	120
Bibliography	124

Figures

Figure 1 — Sketch of the wind tunnel configuration single track ballast (front view, 1:1 scale).....	22
Figure 2 — Sketch of the wind tunnel configuration single track ballast (side and top view, 1:1 scale).....	22
Figure 3 — Illustration of three mass model	24
Figure 4 — Illustration of contact point	28
Figure 5 — Example of the spatial distribution of the wind using a Chinese hat gust model	30
Figure 6 — Illustration of wind decay within Chinese hat gust model	32
Figure 7 — Application of Chinese hat wind scenario: Example of temporal wind distribution for $v_{tr} = 200$ km/h, $v_W = 30$ m/s, vehicle length = 24 m	33
Figure 8 — Illustration of geometric approach considering the angle of attack	36
Figure 9 — Illustration of geometric approach considering the angle of attack of CWC on straight track	37
Figure C.1 — Contour of a wind tunnel model of the ICE 3 endcar	55
Figure C.2 — Contour of a wind tunnel model of the TGV Duplex powercar.....	57
Figure C.3 — Contour of a wind tunnel model of the ETR 500 powercar.....	58
Figure D.1 — Sketch of the wind tunnel configuration flat ground with 235 mm gap	59
Figure D.2 — Sketch of ballast geometry	60
Figure D.3 — Sketch of the embankment geometry	60
Figure D.4 — Sketch of the wind tunnel configuration flat ground without gap	61
Figure D.5 — Ballast and rail configuration for uncanted track in Great Britain.....	62
Figure D.6 — Saw tooth canted ballast and rail in Great Britain.....	62
Figure F.1 — Illustration of embankment overspeed effect.....	76
Figure G.1 — Upper and lower limits for mean velocity profiles.....	78
Figure H.1 — Illustration of five mass model	84

Figure I.1 — Coordinate system.....	98
Figure I.2 — Dependency of f on U_{mean} and U_{max}	100
Figure J.1 — Flow chart of the methodology.....	106
Figure J.2 — Parameters C and m as a function of z_0 for the calculation of X_{L_u} (Couninhan expression).....	108

Tables

Table 1 — Symbols	9
Table 2 — Application of cross wind methodologies for rolling stock assessment	14
Table 3 — Parameter set for the standard ground configuration (standard gauge)	15
Table 4 — Method factor f_m for UIC standard gauge (1 435 mm) for various vehicle types	24
Table 5 — Functions for the Chinese hat gust model.....	34
Table 6 — Form for CWC table for passenger vehicles and locomotives in non-tilting mode.....	38
Table 7 — Form for CWC table for trains in active tilting mode	38
Table 8 — Form for CWC table for freight wagons	39
Table 9 — Layout for plan profile parameters	41
Table 10 — Layout for vertical profile parameters	42
Table 11 — Layout for track design speed.....	42
Table 12 — Layout for wall	43
Table 13 — Layout for line database: meteorological part.....	44
Table 14 — Layout for integrated line database.....	45
Table 15 — Required minimum resolution/accuracy	46
Table A.1 — Application of methodological elements for rolling stock assessment purpose within Europe (aerodynamic assessment)	49
Table A.2 — Application of methodological elements for rolling stock assessment purpose within Europe (vehicle dynamic assessment)	51
Table C.1 — Reference data for aerodynamic coefficients of the ICE 3 endcar model for the ground configuration "single track with ballast and rail" according to 5.3.4.11	56
Table C.2 — Reference data for aerodynamic coefficients of the TGV Duplex powercar model for the ground configuration "single track with ballast and rail" according to 5.3.4.11	57
Table C.3 — Reference data for aerodynamic coefficients of the ETR 500 powercar model for the ground configuration "single track with ballast and rail" according to 5.3.4.11	58
Table E.1 — Benchmark data for aerodynamic coefficients of ICE 3 endcar on flat ground with gap, measured by DB AG on a 1:7-scale model at 80 m/s in DNW wind tunnel	63
Table E.2 — Benchmark data for aerodynamic coefficients of ICE 3 endcar on the windward side on the double track ballast and rail, measured by CSTB on a 1:15-scale model at 50 m/s in CSTB wind tunnel	64
Table E.3 — Benchmark data for aerodynamic coefficients of ICE 3 endcar on the leeward side on the double track ballast and rail, measured by CSTB on a 1:15-scale model at 50 m/s in CSTB wind tunnel	65

Table E.4 — Benchmark data for aerodynamic coefficients of ICE 3 endcar on the windward side of standard embankment of 6 m height, measured by CSTB on a 1:15-scale model at 50 m/s in CSTB wind tunnel	66
Table E.5 — Benchmark data for aerodynamic coefficients of ICE 3 endcar on the leeward side of the standard embankment of 6 m height, measured by CSTB on a 1:15-scale model at 50 m/s in CSTB wind tunnel	67
Table E.6 — Benchmark data for aerodynamic coefficients of TGV Duplex powercar on flat ground with gap, measured by DB AG on a 1:7-scale model at 80 m/s in DNW wind tunnel	68
Table E.7 — Benchmark data for aerodynamic coefficients of TGV Duplex powercar on the windward side on the double track ballast and rail, measured by CSTB on a 1:15-scale model at 25 m/s in CSTB wind tunnel	69
Table E.8 — Benchmark data for aerodynamic coefficients of TGV Duplex powercar on the leeward side on the double track ballast and rail, measured by CSTB on a 1:15-scale model at 25 m/s in CSTB wind tunnel	70
Table E.9 — Benchmark data for aerodynamic coefficients of TGV Duplex powercar on the windward side of the standard embankment of 6 m height, measured by CSTB on a 1:25-scale model at 40 m/s in CSTB wind tunnel	71
Table E.10 — Benchmark data for aerodynamic coefficients of TGV Duplex powercar on the leeward side of the standard embankment of 6 m height, measured by CSTB on a 1:25-scale model at 40 m/s in CSTB wind tunnel	72
Table E.11 — Benchmark data for aerodynamic coefficients of ETR 500 powercar on flat ground with gap, measured by Politecnico di Milano on a 1:10 -scale model at 12 m/s in MPWT wind tunnel.....	73
Table E.12 — Benchmark data for aerodynamic coefficients of ETR 500 powercar on the windward side of the standard embankment of 6 m height, measured by Politecnico di Milano on a 1:10-scale model at 12 m/s in MPWT wind tunnel.....	74
Table E.13 — Benchmark data for aerodynamic coefficients of ETR 500 powercar on the leeward side of the standard embankment of 6 m height, measured by Politecnico di Milano on a 1:10 -scale model at 12 m/s in MPWT wind tunnel.....	75
Table H.1 — Body parameters.....	90
Table H.2 — Secondary suspension parameters	90
Table H.3 — Primary suspension parameters	91
Table H.4 — General parameters	91
Table H.5 — Aerodynamic coefficients	91
Table H.6 — Resulting CWC for example vehicle 1: v_{CWC} in [m/s] depending on the vehicle speed and the unbalanced lateral acceleration a_q at a yaw angle of $\beta_W = 90^\circ$	92
Table H.7 — Resulting CWC for example vehicle 1: v_{CWC} in [m/s] depending on yaw angle β_W and the unbalanced lateral acceleration a_q at $v_{max} = 160$ km/h	93
Table H.8 — Body parameters.....	94
Table H.9 — Secondary suspension parameters	94
Table H.10 — Primary suspension parameters	95
Table H.11 — General parameters	95
Table H.12 — Aerodynamic coefficients	95
Table H.13 — Resulting CWC for example vehicle 2: v_{CWC} in [m/s] depending on the vehicle speed and the unbalanced lateral acceleration a_q at a yaw angle of $\beta_W = 90^\circ$	96

Table H.14 — Resulting CWC for example vehicle 2: v_{CWC} in [m/s] depending on the yaw angle β_W and the unbalanced lateral acceleration a_q at $v_{max} = 200$ km/h	97
Table I.1 — Calculation example for Chinese hat gust scenario with $U_{max} = 30,0$ m/s, $v_{tr} = 200$ km/h, vehicle length = 24 m	102
Table ZA.1 – Correspondence between this European standard, the HS TSI RST, published in the Official Journal on 26 March 2008, and Directive 2008/57/EC.....	120
Table ZA.2 – Correspondence between this European standard, the HS TSI INS, published in the Official Journal on 19 March 2008, and Directive 2008/57/EC.....	121
Table ZA.3 – Correspondence between this European Standard, the CR TSI RST Freight Wagon dated July 2006 and its intermediate revision approved by the Railway Interoperability and Safety Committee on 26 November 2008 and Directive 2008/57/EC	122
Table ZA.4 – Correspondence between this European standard, the CR TSI INF (Final draft Version 3.0 dated 2008.12.12), and Directive 2008/57/EC	122
Table ZA.5 – Correspondence between this European standard, the CR TSI Locomotive and Passenger Rolling Stocks (Preliminary draft Rve 2.0 dated 14 November 2008) and Directive 2008/57/EC.....	123

Foreword

This document (EN 14067-6:2010) 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 July 2010, and conflicting national standards shall be withdrawn at the latest by July 2010.

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 has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association, and supports essential requirements of EU Directive(s).

For relationship with EU Directive(s), see informative Annex ZA, which is an integral part of this document.

This European Standard is part of the series "Railway applications – Aerodynamics" which consists of the following parts:

- Part 1: Symbols and units
- Part 2: Aerodynamics on open track
- 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

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and the United Kingdom.

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 (conventional, tilting, running direction).

1 Scope

This European Standard applies to the cross wind assessment of railways taking into consideration the recommendations given in Annex M on the application of the standard (migration rule). The methods presented have been applied to passenger vehicles with a maximum speed up to 360 km/h and to freight vehicles with a maximum speed up to 160 km/h. This European Standard applies to coaches, multiple units, freight wagons, locomotives and power cars.

2 Normative references

The following referenced documents are indispensable for the application 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 14067-1:2003, *Railway applications — Aerodynamics — Part 1: Symbols and units*

EN 14067-2, *Railway applications — Aerodynamics — Part 2: Aerodynamics on open track*

EN 14363, *Railway applications — Testing for the acceptance of running characteristics of railway vehicles — Testing of running behaviour and stationary tests*

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN 14067-1:2003 and the following apply.

3.1

lee rail

rail on the lee side of the track

3.2

bias

systematic error affecting an estimate

NOTE 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.

4 Symbols and abbreviations

For the purposes of this document, the symbols given in EN 14067-1:2003 and the following apply.

Table 1 — Symbols

Symbol	Unit	Significance	Explanation or remark
$\tilde{A}$	-	Normalized gust amplitude	
a_m	s/m	Dispersion	Dispersion determined by extreme value analysis of wind tunnel data

Table 1 (continued)

Symbol	Unit	Significance	Explanation or remark
a_q	m/s ²	Uncompensated lateral acceleration	
A_{xz}	m ²	Reference side area of the model vehicle	The side area of the model vehicle
A_0	m ²	Reference normalisation area	10 m ²
b_A		Lateral contact spacing	
$b_{A,min}$		Minimum lateral contact spacing	
c_{Fi}	-	Non-dimensional force coefficient based on A_0	$c_{Fi} = \frac{2 \cdot F_i}{\rho \cdot v^2 A_0}$, $i = x, y, z$
c_{Mi}	-	Non-dimensional moment coefficient based on A_0 and d_0	$c_{Mi} = \frac{2 \cdot M_i}{\rho \cdot v^2 A_0 d_0}$, $i = x, y, z$
$c_{Mx,lee}$	-	Non-dimensional rolling moment coefficient around leeward rail	
$c_{Mx,lee,bmk}$	-	Benchmark value of rolling moment coefficient around leeward rail	Rolling moment coefficient determined from the benchmark tests
d_0	m	Reference normalisation length	3 m
F	Hz	Frequency	
f_h		Function of the embankment blockage ratio, B_E	
$f_{\Delta Q}$	-	Relative windward wheel unloading factor	0,9
f_m		Method factor	To account for uncertainties in the 3 mass model.
h	m	Vehicle height	
h_{cant}	m	Cant	
h_{VEH}	m	Height of the vehicle from top of rail to roof	
h_{BL}	m	Boundary layer height	
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
L	m	Vehicle length	
L_{VEH}	m	Length parameter of the vehicle car body	
$^x L_i$	m	Longitudinal integral length scale of the i -wind velocity component along the x direction	$i = u, v, w$

Table 1 (continued)

Symbol	Unit	Significance	Explanation or remark
${}^yL_i$	m	Lateral integral length scale of the i-wind velocity component along the y direction	$i = u, v, w$
${}^xL_u$	m	Turbulence length scale	Longitudinal streamwise velocity turbulence length scale in the core stream
${}^xL_{u_FS}$	m	Full scale turbulence length scale	
M_m	Nm	Restoring moment due to the vehicles masses	
M_{la}	Nm	Moment due to uncompensated lateral acceleration	
M_{CoG}	Nm	Moment due to the lateral movement of the centre of gravity of suspended masses	
$M_{x,lee}$	Nm	Rolling moment around leeward rail	
m	kg	Vehicle mass (to be considered for cross wind assessment)	Refers to operational mass in working order according to EN 15663
m_0	kg	Unsprung masses	Refers to operational mass in working order according to EN 15663
m_1	kg	Primary suspended masses	Refers to operational mass in working order according to EN 15663
m_2	kg	Secondary suspended masses	Refers to operational mass in working order according to EN 15663
ΔQ	N	Wheel unloading	
Q_0	N	Average static wheel load	
$\Delta Q/Q_0$	-	Relative wheel unloading	
R_C	m	Radius of curve	
Re_{max}		Maximum Reynolds number	The maximum achievable Reynolds number in a wind tunnel test
S_U	$m^2/s^2/Hz$	Power spectral density	
S_t	-	Model time scale	The ratio of time at model scale to time at full scale
T_{samp}	s	Data acquisition duration	The sampling duration for acquiring data
Tu_x		Turbulence level	$Tu_x = \left(\overline{u'^2} / \bar{u}^2 \right)^{0.5}$

Table 1 (continued)

Symbol	Unit	Significance	Explanation or remark
U_{mean}	m/s	Mean wind speed	Refers to the upwind at 4 m height above ground
U	m/s	Wind (tunnel) velocity	
$U(t)$	m/s	Instantaneous wind (tunnel) velocity	
U_{turb}	m/s	Wind velocity turbulent component along the mean wind direction	
v_a	m/s	Relative wind velocity	
v_{max}	m/s	Maximum train speed	
v_W	m/s	Wind speed	
V_x	m/s	Magnitude of wind speed vector	Refers to the upwind at 4 m height above ground
x_B	%	Blockage ratio at $\beta = 30^\circ$	Total modelled configuration projected side area to the wind tunnel cross section
y_B	m	(Maximum) displacement of the contact point on the wheel in the wheel flange direction	
z	m	Height from the ground	
z_{CoG}	m	Height of the centre of gravity of the total vehicle	
$z_{\text{CoG},0}$	m	Height of the centre of gravity of the unsprung masses	
$z_{\text{CoG},1}$	m	Height of the centre of gravity of the primary suspended masses	
$z_{\text{CoG},2}$	m	Height of the centre of gravity of the secondary suspended masses	
z_0	m	Roughness height	
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
$\delta_{99\%}$	m	Boundary layer thickness	z coordinate at which the local velocity equals 99 % of the free stream velocity
ε_{max}		Maximum tolerance target value	
$\varepsilon_{\text{mean}}$		Mean tolerance target value	
ρ_0	kg/m ³	Reference air density	$\rho_0 = 1,225 \text{ kg/m}^3$

5 Methods 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 of attack, the resulting set of characteristic wind speeds is called the characteristic wind curves (CWC).

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.

It has to be noted that the CWC 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 CWC define the maximum natural wind speed 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.

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.

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

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

Subclause 5.4 provides various methods for the determination of wheel unloading.

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

5.2 Applicability of cross wind methodologies for rolling stock assessment purposes

Subclauses 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 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.

In case of 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	$v_{\max} \leq 140$ km/h	140 km/h < $v_{\max} \leq 200$ km/h	200 km/h < $v_{\max} \leq 360$ km/h ^a	$v_{\max} \leq 80$ km/h	80 km/h < $v_{\max} \leq 160$ km/h
Simplified proof of cross wind stability	Yes, Regulated by national requirements (see Annex K for more information).	Yes, Subclause 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, Subclause 5.3.4 + 5.4.2 <u>Restrictions:</u> 5.4.2 not applicable for articulated trains	Yes, Regulated by national requirements (see Annex K for more information).	Yes, Subclause 5.3.2 + 5.4.2 or 5.3.3 + 5.4.2
Full proof of cross wind stability	No	Yes, Subclause 5.3.4 + 5.4.3 or 5.3.4 + 5.4.4	Yes, Subclause 5.3.4 + 5.4.3 or 5.3.4 + 5.4.4	No	Yes, Subclause 5.3.4 + 5.4.2 or 5.3.4 + 5.4.3

^a Above 360 km/h the methods shall be adapted taking into account also compressibility effects.

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 Computation Fluid Dynamics (CFD) simulations are often used for feasibility studies in the early vehicle design process. Data obtained with predictive equations are usually used for a first analysis. The following subclauses describe how these methods are to be applied. Table 2 indicates their applicability for rolling stock assessment purposes.

5.3.2 Predictive equations

The predictive equations can only be used subject to the following restrictions:

- The method may not be valid for vehicles which differ much in their shape from the shape of current vehicles.
- The method is not valid for leading end cars with a length L greater than 28 m or less than 10 m.

- The method is not valid if the car(s) leading the investigated intermediate car have an overall total length of less than 10 m.
- The method is valid only for standard track gauge of 1,435 m.

The equation was chosen to be conservative and therefore should not underestimate 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 EN 14067-1, 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 (predictive equations).

The predictive equations allow the wind load to be calculated as follows:

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

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

when the parameters $z_0, z_1, z_2, z_3, z_4, z_5, f_L$, and f_{VEH} are given (see Table 3). $c_{Mx,lee}$ is based on A_0 and d_0 , this normalization differs from EN 14067-1.

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

Parameter	Passenger vehicle (leading endcar) and locomotive	Passenger vehicle (midcar)	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	$4,3 \cdot 10^{-3}$		For $0^\circ \leq \beta \leq 40^\circ$: $z_1 = 0,01375$ For $\beta > 40^\circ$: $z_1 = 0$
z_2	$2,2 \cdot 10^{-4}$		0
z_3	$-2,1 \cdot 10^{-6}$		0
z_4	1,2		1
z_5	1,2		1
L_{VEH}	Length of the vehicle car body without buffer and inter car gap		Length over buffer
f_L	$f_L = 2 - \frac{L_{VEH}}{L_0}$ with $L_0 = 25 \text{ m}$	1	1
f_{VEH}	1	0,75	1
A_0	10 m^2		
d_0	3 m		
β	Yaw angle in degrees		
h_{VEH}	Height of the vehicle from top of rail to roof according to EN 14067-1		

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 according to EN 14067-1. In addition, CFD provides a prediction of the velocity and pressure fields, and easily allows different configurations to be taken into account.

NOTE Those undertaking CFD simulations and analysis of the results should be able to demonstrate competency through a proven record of railway aerodynamic simulations and have knowledge of vehicle aerodynamics.

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 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 equations 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, steady methods may be used if the steadiness of the flow is evident. One commonly applied criterion 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 large enough 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 vehicle model shall be according to that for wind tunnel measurements, see 5.3.4.8 and 5.3.4.9, as far as intercar-gaps, vehicles lengths and modelling accuracy are concerned for the test vehicle and adjacent vehicles.

Contact between the wheels and rail or ground may be simplified 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 on 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 wall units 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 should 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 about the lee rail should have an accuracy of 3 % between the three refinements for each yaw angle in the range of interest. 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 equations (Navier-Stokes equations) but methods based on kinetic gas theory (Lattice-Boltzmann equations) 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 non-linear convection terms of the governing flow equations. 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.

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 at 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 is based on the flow speed at the onset boundary and 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 has to 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 about 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 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 roll over.

NOTE Those undertaking wind tunnel testing and analysis of the results should be able to demonstrate competency through a proven record of aerodynamic testing in wind tunnels and have knowledge of vehicle aerodynamics.

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 tunnel operators. 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.

It is permissible to use different types of wind tunnels. Details of the wind tunnel used shall be described according to EN 14067-2.

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 endcar, TGV Duplex powercar or ETR 500 powercar (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 benchmark test should be conducted using the same techniques, configurations, onset wind conditions, equipment etc. as the tests for the new vehicles. These benchmark tests shall be repeated if there is any change in the wind tunnel set-up (e.g. in wind tunnel, re-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. They will also show any systematic bias in the coefficients compared with the reference results. Exact agreement is not expected due to differences between different wind tunnels and experimental set-ups. The required tolerances for low turbulence tests are:

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

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

Good target tolerance values have been found to be $\varepsilon_{\max} = 0,15$ 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 respected, modifications should 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:

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

with u denoting the streamwise velocity component.

5.3.4.4 Boundary layer

The wind tunnel velocity profile shall be 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 measured vehicle shall be less than 30 % of the vehicle height. Boundary layer thickness has to be determined without train and without ground model present.

5.3.4.5 Reynolds number

The Reynolds number based on the wind tunnel speed, 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 $c_{Mx,lee}$

for at least one configuration for each vehicle tested should be documented over the range $[0,6 Re_{max}, Re_{max}]$.

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 total modelled configuration (train model + embankment if present) projected side area to the wind tunnel cross section. 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 %. 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 are 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 minimised.

5.3.4.9 Modelling accuracy

The live vehicle should 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 should be modelled to a tolerance of - 0,5 % and + 1 % of a given dimension of the body shape. Smooth curved surfaces should 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 should be modelled. The surface of the model should be generally smooth, but where there are localised regions of surface roughness on the vehicle these should be simulated. It is less important to model the under body of the train correctly, however the general shape of the under body and the blockage in the bogie region should be represented. The wheels shall be flattened to prevent contact with the ground. The pantograph should in general not 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.

It is recommended to build a symmetrical model, 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 should be performed with both positive and negative yaw angles.

5.3.4.10 Instrumentation requirements

The required moment and force coefficients are 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.

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

Force and moment balance

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

The model should 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 should be undertaken. Demonstration of the system dynamic response should be provided in the test documentation.

Calculation of air density

The air density ρ should be calculated from the average measured temperature, and pressure for each (data acquisition) test using the ideal gas law with an 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 ballast profile and the rails should be provided, to the following level of detail: the underlying shape should be modelled to ± 5 cm full scale and features with full-scale dimensions greater than 10 cm should be modelled. Any smaller features should be modelled as generalised roughness. Notwithstanding the above, individual ballast stones should not be modelled.

Particular care should be taken with the height of the vehicle relative to the rails so that this is accurate to ± 5 cm full scale. The height should 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). Sketches for the reference configuration of single track ballast are shown in Figure 1 and Figure 2.

Dimensions in millimetres

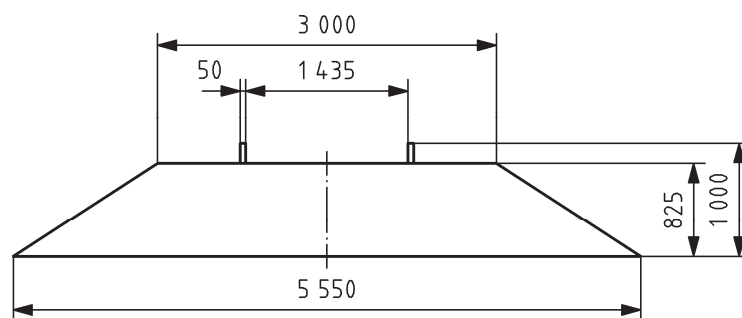
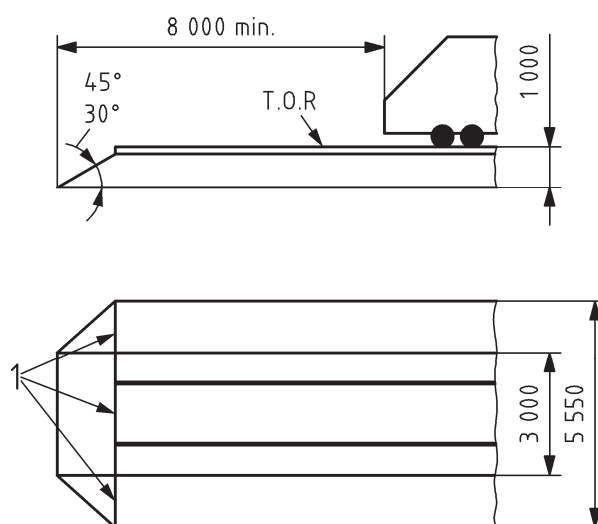


Figure 1 — Sketch of the wind tunnel configuration single track ballast (front view, 1:1 scale)

Dimensions in millimetres



Key

- 1 edge rounding $R = 300$

Figure 2 — 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 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 should be made at a sufficient yaw angle resolution. 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, current (and additional) interoperability requirements are set out in Annex A. An overview of test requirements for other approaches is also given in Annex A.

5.3.4.13 Data interpolation

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

5.3.4.14 Documentation

Conformity with all requirements defined in 5.3.4 has to be documented.

5.4 Determination of wheel unloading

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 using a two-dimensional vehicle model (three mass model)

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. This modelling shall be appropriate and conservative.

5.4.2.2 General approach

For the calculation of the characteristic wind speed the moment of equilibrium towards the leeward 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 EN 14067-1 with the exception of the wind from the right in the direction of travel (see Figure 3) the moment of equilibrium towards the leeward (left) rail is given by:

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

The factor $f_{\Delta Q}$ 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 is larger than 1,0 and for UIC standard gauge (1 435 mm) it shall be chosen according to Table 4.

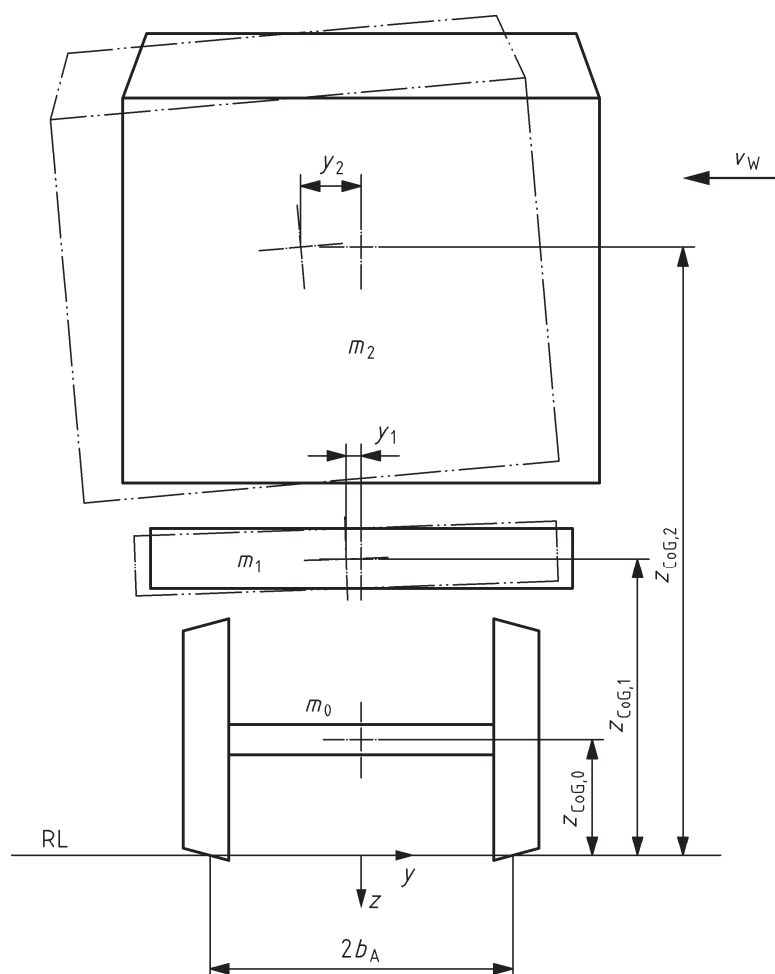


Figure 3 — Illustration of three mass model

Table 4 — Method factor f_m for UIC standard gauge (1 435 mm) for various vehicle types

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

The moments in Equation (5) are calculated according to Equations (6) to (11).

$$M_m = m \cdot g \cdot b_A \quad (6)$$

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

$$M_{la} = m \cdot a_q \cdot z_{CoG} \quad (8)$$

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 UIC standard gauge) $2b_A = 1,5$ m;
- the uncompensated lateral acceleration a_q ; for a particular curve of radius R_c [m] with cant h [m];

$$a_q = \frac{v_{tr}^2}{R_c} - \frac{gh}{2b_A}$$
 $(R_c \text{ positive for curve to the right, positive value for } h \text{ results in rotation of track in direction of } x);$
- the height of the centre of gravity of the unsprung masses $z_{CoG,0}$ (usually the wheel radius);
- the height of the centre of gravity of the primary sprung masses $z_{CoG,1}$;
- the height of the centre of gravity of the secondary suspended masses $z_{CoG,2}$;
- the height of the centre of gravity of the total vehicle $z_{CoG} = \left(\frac{m_0 \cdot z_{CoG,0} + m_1 \cdot z_{CoG,1} + m_2 \cdot z_{CoG,2}}{m} \right)$.

NOTE Data (such as height of roll centre, maximum lateral displacement distances, flexibility coefficient (suspension coefficient) needed for the calculation of y_1 and y_2 may be obtained from the assumptions given in the gauge calculation of the vehicle according to EN 15273-2:2009.

The aerodynamic moment induced by the wind is:

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

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

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

$$v_a^2 = (v_w \cdot \cos \beta_w + v_{tr})^2 + v_w^2 \cdot \sin^2 \beta_w \quad (10)$$

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

Equations (5) to (11) have to be solved to obtain values for the characteristic wind speed v_W (v_{tr} , a_q , β_W). This may be done by 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 utilising 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 equations which can be determined using MBS codes or by explicit formulation of the equations.

5.4.3.2 Computation method

In this method, a quasi-static approach is used for the calculation of characteristic wind curves (CWC) 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 non-linear 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 cars 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 (CWC). A simple model (five mass model) is suitable for many vehicles. A simplified vehicle-specific MBS model can 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 cars. 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 equations of a simple five mass model is given in Annex H. The subsequent CWC calculation can 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 are to be compared with the measurements (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 calculation. 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 simplified MBS model has to be modified. Modifications of the simplified MBS model will need to be verified according to the above.

5.4.3.4 Calculation of 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 have to 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, neglecting the drag coefficient c_{FX} .

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

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

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

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

The relative airflow velocity is calculated from the wind speed, the train speed and the angle between the wind and track direction according to EN 14067-1.

The relative flow velocity and the yaw angle are calculated as follows (see also EN 14067-1):

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

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

When calculating the wheel-rail forces (Q -forces), the displacement of the contact point in the wheel flange direction shall be considered (see Figure 4).

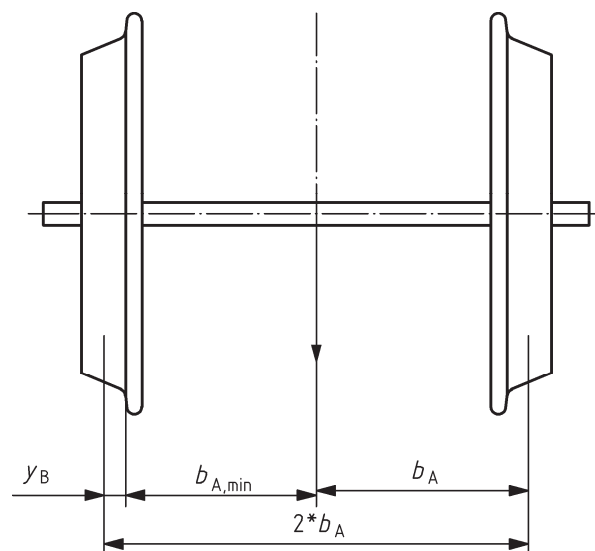


Figure 4 — Illustration of contact point

The value $b_{A,min}$ results from the width between the supports

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

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

$$y_B = 0,028 \text{ m (for nominal track gauge 1 435 mm)} \quad (17)$$

so

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

For the calculation of the characteristic wind curves, the equilibrium position has to be calculated for different wind speeds. The definition of the characteristic wind speed is that wind speed which leads to 90 % wheel unloading (i.e. a residual load of 10 % of Q_0).

5.4.3.5 Process verification

The implementation has to be proven by a process verification.

If the typical five mass model is used, each CWC calculation for a vehicle should 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 (operational mass in working order according to EN 15663). 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 shifts), 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 be modelled too.

Track irregularities shall not be considered.

For the assessment of interoperable rolling stock, 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 will be used for assessment against the limits. For the assessment of other rolling stock, the calculation shall be done with the gauge used.

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 equation:

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

The CWC obtained refer 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 equations 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 ~ 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 5).
- The mean wind is assumed to be horizontal; only the along wind component U 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 wind speed,

β_W wind direction with respect to the line.

The following parameters are fixed:

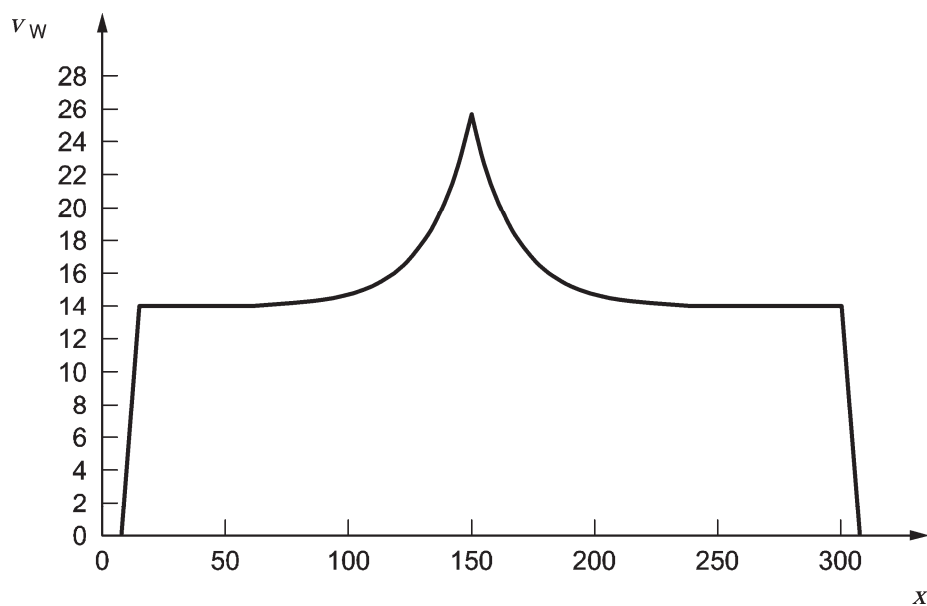
$z = 4$ m reference height,

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

$z_0 = 0,07$ 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 (CWC), the spatial distribution of the wind is described with a mathematical model, with the shape plotted in Figure 5.



Key

x space, in m

v_W wind speed, in m/s

Figure 5 — 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:

$$U_{\text{mean}} = \frac{U_{\text{max}}}{1,6946} \quad (20)$$

The power spectral density is calculated from:

$$S_u(n) = \frac{22,9839 \text{ m} \cdot U_{\text{mean}}}{\left(1 + 652107 \text{ m}^2 \cdot \left(\frac{n}{U_{\text{mean}}}\right)^2\right)^{\frac{5}{6}}} \quad (21)$$

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

The characteristic frequency f for of the gust is the integral:

$$f = 0,239091 \cdot \left[\frac{\int_{1/300}^1 n^2 \cdot S_u(n) dn}{\int_{1/300}^1 S_u(n) dn} \right]^{0,5} \quad (22)$$

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

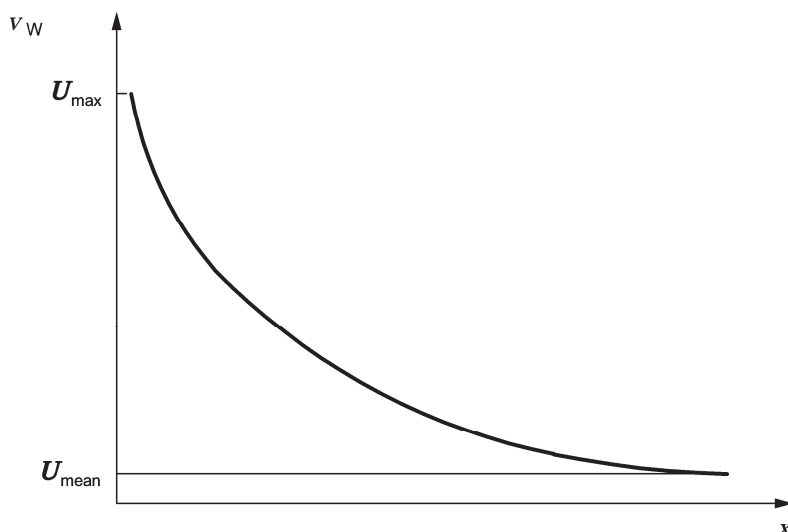
The wind speed normal to the vehicle along the track can be calculated from:

$$v_{W-90} = U_{\text{mean}} \cdot (1 + 0,6946 \cdot C_{90}) \quad (23)$$

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

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 6):



Key

x space

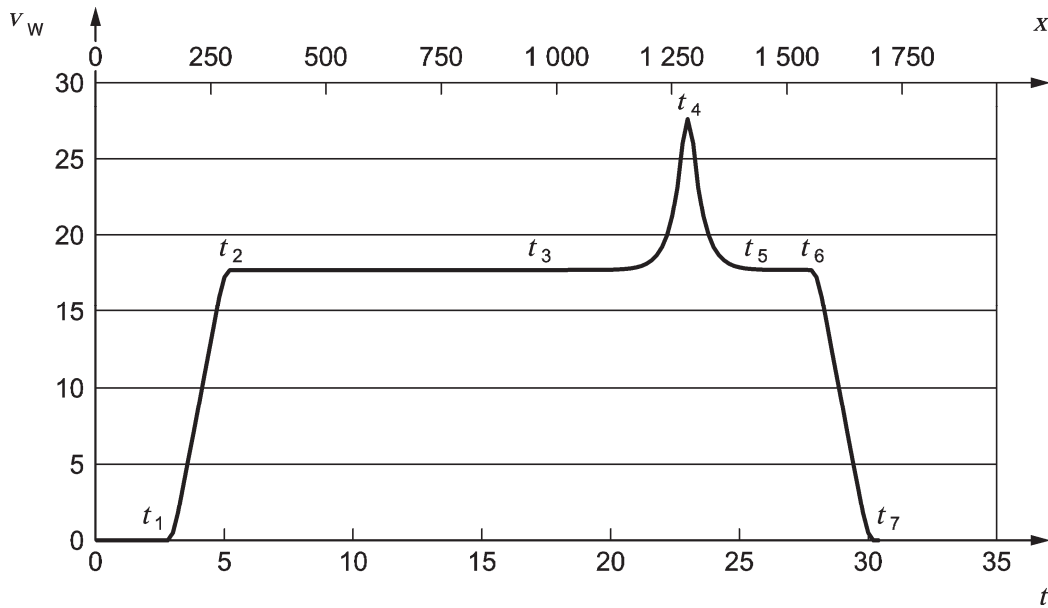
v_W wind speed

Figure 6 — Illustration of wind decay within Chinese hat gust model

For practical implementation, the exponential decay is assumed to have reached the lower limit if there is less than 1 % deviation between U_{mean} and the calculated wind speed. For the complete representation of the Chinese hat, mirroring is necessary in the y axis.

The wind gust shall be low-pass filtered using a moving spatial average based on a window size equal to the vehicle length and a step size smaller than 0,5 m.

The scenario consists of a base level wind speed, followed by the rising wind speed part of the Chinese hat. This is then followed by the decaying part and then the base level wind speed once again. In order to get repeatable results in the time-dependent MBS simulations, the vehicle has to be in a steady wind load state. For this reason the scenario consists of the following in terms of temporal distribution (see Figure 7, example as in Annex I, I.2):



Key
 x , in m
 v_W , in m/s
 t , in s

Figure 7 — Application of Chinese hat wind scenario: Example of temporal wind distribution for $v_{tr} = 200$ km/h, $v_W = 30$ m/s, vehicle length = 24 m

Up to t_1 there is no wind. From t_1 to t_2 there is a linear rise until the base level U_{mean} is reached. The vehicle has to be in a steady wind loading state between t_2 and t_3 , before the second rise of the wind speed begins. For this either the constant value of the base level may be applied or the mirrored Chinese hat scenario with a deviation between U_{mean} and the calculated wind speed of less than 1 % may be used. After t_3 the rise follows the mirrored Chinese hat up to the maximum at t_4 . After the maximum, the wind decays according to the Chinese hat function to t_5 . Time t_6 can be chosen equal to t_5 . In case t_6 is chosen $t_6 \neq t_5$, the wind stays at the base level once again from t_5 to t_6 . From t_6 on there is a linear fall, until at t_7 the wind scenario is finished. The wind scenario in the different intervals is described by the functions given in Table 5:

Table 5 — Functions for the Chinese hat gust model

Interval	Function
$[t_0:t_1]$	$u(t) = 0$
$[t_1:t_2]$	$u(t) = \frac{U_{\text{mean}}}{t_2 - t_1} \cdot (t - t_1)$
$[t_2:t_3]$	$u(t) = U_{\text{mean}}$
$[t_3:t_4]$	$u(t) = \text{mirrored Chinese hat; } t_3: \text{ deviation between } U_{\text{mean}} \text{ and the calculated wind speed of less than 1 \%}$
$[t_4:t_5]$	$u(t) = \text{Chinese hat; } t_5: \text{ deviation between } U_{\text{mean}} \text{ and the calculated wind speed of less than 1 \%}$
$[t_5:t_6]$	$u(t) = U_{\text{mean}}$
$[t_6:t_7]$	$u(t) = \frac{U_{\text{mean}}}{t_7 - t_6} \cdot (t_7 - t)$

For articulated trains, vehicles with Jacobs bogies or similar solutions with transmission of roll moments between car bodies, one single gust is considered and each car body will be submitted to either the mean wind or the gust. As the gust is being fixed in space there will be a time delay between the application of the forces and the moments resulting from the gust acting on each vehicle. This time delay depends on the distance between two adjacent car bodies and the train speed. This distance is defined as the distance of the geometrical centres (considered longitudinally) of two adjacent car bodies.

Filtering of the gust has to be done separately for each car body considering the length of this car body.

The specific scenario for articulated train set can be defined on the basis of the one presented in Figure 5. Up to t_1 there is no wind applying onto the train, from t_1 to t_2 there is a linear rise until the base level U_{mean} is reached. All the vehicles of the train have to be in the steady wind loading state between t_2 and t_3 , before the second rise of the wind speed begins. After t_3 , the rise follows the mirrored Chinese hat until t_4 . After the maximum, the wind decays according to the Chinese hat function to t_5 . Time t_6 is reached when the rear of the last vehicle of the train is again fully submitted to the mean wind.

5.4.4.3 Vehicle model setup

The modelling of the vehicle shall be adequate for the investigation of cross wind characteristics. The dynamic model of the vehicle shall be 3D and shall incorporate at least the following features:

- Car body, bogies and wheel sets and other relevant parts of the vehicle (masses, inertias, position of centres of gravity);
- Suspensions (stiffness of the springs in the vertical, lateral and longitudinal directions, non-linearity in stiffness, damping characteristics in the vertical and lateral directions, damping non-linearity, position);
- Bump stops which could come into play;
- Wheel/rail contact, contact forces calculated featuring nonlinear contact geometry and creep force/creep relation. Any special further device in the suspension system which might have an effect on the overturning mechanism.

5.4.4.4 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 are to be compared with the measurements (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 calculation. 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 has to be modified. Modifications of the MBS model will need to be verified according to the above.

5.4.4.5 Input of aerodynamic forces and moments

Calculations of the vehicle responses to gusts defined by their maximum speed $U_{\max}$ shall be computed for increasing values of $U_{\max}$ until the criterion of unloading is met. The corresponding plots of $U_{\max}$ values, which just cause maximum unloading criterion to be met, against the vehicle speed and/or wind angle are called characteristic wind curves (CWC). The presentation of CWC is described in detail in 5.5.

The simulation of the vehicle response to a gust shall be performed using the gust scenario described in 5.4.4.2.

The five components of forces and moments (F_y , F_z , M_x , M_y and M_z) shall be calculated using the following equations:

$$\left. \begin{aligned} F_i(t) &= \frac{1}{2} \rho A_0 c_{Fi}(\beta(t)) v_a^2(t) \\ M_i(t) &= \frac{1}{2} \rho A_0 d_0 c_{Mi}(\beta(t)) v_a^2(t) \end{aligned} \right\}, i \in \{x, y, z\} \quad (25)$$

$$\left. \begin{aligned} v_a(t) &= \sqrt{(v_{tr} + v_w(t) \cos \beta_w)^2 + (v_w(t) \sin \beta_w)^2} \\ \beta(t) &= \arctan \left(\frac{v_w(t) \sin \beta_w}{v_{tr} + v_w(t) \cos \beta_w} \right) \end{aligned} \right\} \quad (26)$$

It shall be proven that the integration method calculates an integration step at the maximum wind peak. The output step size of the calculation shall be lower than 1/30 s.

5.4.4.6 Calculation of CWC

5.4.4.6.1 Evaluation of the criterion

From each simulation run of the parameter variation time data of the Q -forces for each wheel are obtained.

The following calculation steps are needed:

- Calculation of the $\Delta Q/Q_0$ values by the time-data of Q -forces:

$$\frac{\Delta Q}{Q_0} = 1 - \frac{Q_{i1} + Q_{j1}}{2 \cdot Q_0} \quad (27)$$

- Low-pass filtering of $\Delta Q/Q_0$ with a 2 Hz 4th order Butterworth filter, or another filter shown to be equivalent.
- Identification of the maximum $\Delta Q/Q_0$ value over the running gear.

Herein Q_0 are the Q -forces for the empty (unloaded) vehicle without any excitation, Q_{i1} are the Q -forces of the unloaded wheel of the first wheel set in the bogie and Q_{j1} are the Q -forces of the unloaded wheel of the second wheel set in the bogie.

5.4.4.6.2 Calculation of the effect of curves

For curved track the centrifugal force is assumed to act in addition to the crosswind on the vehicle.

The calculation shall be performed using MBS on straight track, canted according to a_q values.

5.4.4.6.3 Relative wind-angle decomposition method

For trains that do not show strong vehicle dynamic dependence with train speed, the computed characteristic wind velocities can be transferred to other combinations of train speeds and angles.

Usually the characteristic wind velocity is given for a wind angle of 90° to the track. To obtain the CWC for other wind angles, train speeds and wind speeds, a geometric decomposition/addition of the velocity vectors has to be carried out first (see Figure 8).

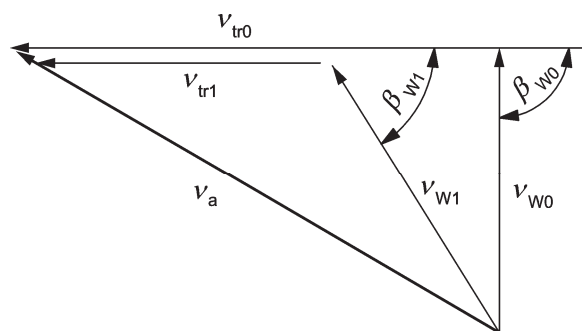
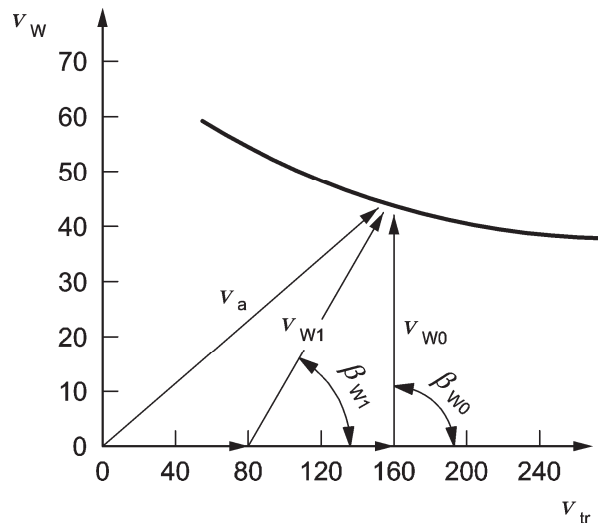


Figure 8 — Illustration of geometric approach considering the angle of attack

Here, v_a is the resultant wind acting on the vehicle. A decomposition of v_a into a component coming from the train speed (v_{tr0} and v_{tr1}) and a component coming from the wind speed (v_{w0} and v_{w1}) can be made in various ways. For the vector chain v_{w0} and v_{tr0} the wind angle is β_{w0} , and for the vector chain v_{w1} and v_{tr1} the wind

angle is β_{W1} . For straight track, the wind velocity for different angles of attack can be directly drawn out in a diagram. An example is illustrated in Figure 9. Here $\beta_{W1} = 60^\circ$ and $\beta_{W0} = 90^\circ$.



Key

v_{tr} vehicle speed v_{tr} , in km/h
 v_W wind speed, in m/s

Figure 9 — Illustration of geometric approach considering the angle of attack of CWC on straight track

5.5 Presentation form of characteristic wind curves (CWC)

5.5.1 General

The CWC of a train is needed to help a railway operator to evaluate whether the train's operation on a line is safe. For this purpose, train builders shall give the CWC that their train has to withstand. Subclause 5.5.2 presents the requirements for vehicles other than freight wagons, subclause 5.5.3 presents the requirements for freight wagons.

5.5.2 CWC presentation form for passenger vehicles and locomotives

The CWC presentation form shall include the following information:

- vehicle type and main dimensions,
- whether vehicle is in active tilting or non-tilting mode,
- method used to determine the aerodynamic coefficients (prediction formula, CFD, wind tunnel tests),
- vehicle dynamic method used to compute the CWC (simple quasi-static method, advanced quasi-static method, time-dependent multi-body simulation),
- track configuration (standard gauge or alternative) and rail inclination.