Railway applications — Methods for calculation of stopping and slowing distances and immobilisation braking

Part 6: Step by step calculations for train sets or single vehicles

ICS 45.060.01

British Standards

National foreword

This British Standard is the UK implementation of EN 14531-6:2009.

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

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Foreword

This document (EN 14531-6:2009) 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of an identical text or by endorsement, at the latest by November 2009, and conflicting national standards shall be withdrawn at the latest by November 2009.

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 Standard[1] is one in a series of six, under the generic title EN 14531, Railway applications — Methods for calculation of stopping distances, slowing distances and immobilization braking. The other five are:

Part 1: General algorithms;

Part 2: Application to Single Freight Wagon (in preparation)*;*

Part 3: Application to mass transit (in preparation)*;*

Part 4: Single passenger coaches (in preparation)*;*

Part 5: Locomotives (in preparation).

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 2008/57/EC.

For relationship with EU Directive 2008/57/EC, see informative Annex ZA, which is an integral part of this document.

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, 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.

[1] Although it was originally intended to prepare a series of six parts for this Standard, the intention is now to rationalize and restructure the Standard so that it comprises fewer parts.

Introduction

The objective of this European Standard is to enable the railway industries and operators to work with a common calculation method.

It describes the adapted algorithms and step-by-step calculations for the design of brake equipment for all types of train sets, electrical multiple units, diesel multiple units and single vehicles.

1 Scope

This European Standard describes a general algorithm that may be used in all types of high speed and conventional vehicle applications, including self-propelling thermal or electric trains, thermal or electric traction units; passenger carriages, mobile railway infrastructure construction and maintenance equipment and freight wagons. This standard does not specify the performance requirements. It enables the calculation of the various aspects of the performance: stopping or slowing distances, dissipated energy, force calculations and immobilization braking.

This standard enables the verification by calculation of the stopping, slowing and immobilization performance requirements for high speed and conventional trains operating on high speed and conventional infrastructure.

Other calculation methods may be used providing that the order of accuracy achieved is in accordance with this European Standard.

This standard presents:

a) example of distance and other dynamic calculations, see Annex C;

b) example of immobilisation calculations, see Annex D.

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 14478:2005, *Railway applications — Braking — Generic vocabulary*

EN 14531-1:2005, *Railway applications — Methods for calculation of stopping distances, slowing distances and immobilization braking — Part 1: General algorithms*

prEN 15328, *Railway applications - Braking - Brake pads* [2]

ISO 80000-3:2006, *Quantities and units — Part 3: Space and time*

ISO 80000-4:2006, *Quantities and units — Part 4: Mechanics*

3 Definitions, symbols and abbreviations

3.1 Terms and definitions

For the purposes of this document, the definitions given in EN 14478:2005, EN 14531-1:2005, ISO 80000-3:2006, ISO 80000-4:2006, and the following apply.

3.1.1
static mass per axle
(1) mass, measured by weighing at the wheel-rail interface, or estimated from design evaluation of each axle in a stationary condition

2 At the time of publication, this Standard was in the process of being prepared.

(2) mass of the train divided by the quantity of axles in case where the static mass per axle is not known

3.1.2
static mass of the train
summation of all the static mass per axle values, including all operating loads

3.1.3
brake equipment type
group of equipment the purpose of which is to provide braking force

3.1.4
isolated brake equipment
status of inoperable brakes on e.g. bogie (see EN 14478)

3.1.5
active brake equipment
equipment considered during the calculation of a specific type of braking (in opposition with isolation) (see EN 14478)

3.1.6
step by step calculation
numerical method with finite time steps

NOTE Synonym for a numerical type of solving an integral.

3.2 Symbols and indices

For the purposes of this document, the general symbols given in Table 1 and indices given in Table 2 apply.

NOTE Specific symbols and indices are defined in the relevant clauses.

Table 1 — Symbols

Symbol	Definition	Unit
A	area	m^2
A_s	swept area of a friction surface	m^2
a	deceleration	m/s^2
B	braked weight	t
D	wheel diameter	m
d	diameter	m
F	force	N
F_B	braking force	N
F_g	downhill force on the train	N
f	coefficient of friction	-
g_n	standard acceleration of free fall = 9,80665 m/s^2 (refer to ISO 80000-3)	m/s^2
i	gradient [a]	-
i_C	cylinder ratio	-
i_{rig}	rigging ratio	-
i_{tra}	transmission ratio	-
m	mass	kg
n	quantity	-
P	power	W
p	pressure	Pa
R	wheel radius	m
r	radius	m
s	distance	m
S	safety factor	-
t	time	s
τ	coefficient of adhesion	-
v	speed	m/s
W	energy	J
W_S	energy per square unit	J/m^2
λ	brake percentage	-
μ	coefficient of friction (brake pad or blocks)	-
η	efficiency	-
[a] Rising gradient is positive; e.g. for a gradient of 5 ‰ i = 0,005.		

Table 2 — General indices

Symbol	Term
AMG	attraction force for a magnetic track brake
ax	axle
a	available
B	friction
BEC	braking force for an eddy current brake
BED	electro-dynamic braking force
BFR	fluid retarder braking force
BMG	braking force for a magnetic brake
b	block or pad
bog	bogie
C	cylinder
cha	characteristic
Bd	brake force demand
disc	disc
dyn	dynamic
e or 2	final
e	equivalent
ext	external
H	hand brake
i	brake equipment type
im	immobilization, parking, holding
int	internal
inst	instantaneous
m	average, mean
max	maximum
min	minimum
mot	motor
m_unsp	unsprung mass
MG	magnetic brake
n	normal direction
r	responsen
Ra	train resistance to motion
req	required
rig	rigging
rot	rotating
R1	return spring
R2	regulator
S	spring
st	static
t	tangential direction
tot	total
tra	transmission
wind	wind
0 or 1	initial

4 General algorithms

4.1 General algorithm to calculate stopping and slowing distances

This algorithm is presented in Figure A.1

This algorithm shall be used with instantaneous values which are calculated step by step. The numerical integration shall be time based (see 5.8). A rough estimation can be based on EN 14531-1. The rough estimation shall only be used to check the results of the numerical integration.

The content of each algorithm, the corresponding definitions of input values and different phases of calculation are given in Clause 5.

4.2 General algorithm to calculate immobilization brake

This algorithm is presented in Figure A.2.

The content of each algorithm, the corresponding definitions of input values and different phases of calculation are given in Clause 6.

5 Stopping and slowing distances calculation

5.1 Accuracy of input values

The accuracy of the calculation described here depends directly on the accuracy of the input data. All the input data shall have an appropriate order of accuracy and shall be justified by tests, further calculations or engineer's estimations, etc.

Corresponding calculations or test reports (or extracts of these documents) should be attached with the performance calculation.

5.2 General characteristics

5.2.1 Train formation

The parameters which shall be used to define train formation are:

a) quantity of motor axles;

b) quantity of trailer axles;

c) quantity of braked axles for each adhesion dependent brake equipment type;

d) quantity of non-adhesion dependent brake equipment type.

According to the braking system design, the parameters can also be defined at the level of the bogies, or of the vehicles.

Calculations shall be performed for each brake equipment type. In so doing, the brake force contributions from each of the brake equipment subtypes (e.g. disc brakes, tread brakes, electrodynamic brakes) shall be taken into consideration. All of the various types of brake equipment applied to one axle shall be identified and accounted for in the calculation.

NOTE 1 When there are several brake equipment types, it is preferable to identify each type (for example by means of a number: type 1, type 2, etc.).

When brake equipment is used on one part of the train under certain conditions and used on another part under different conditions (for example with two different cylinder pressures for the same load level), two different brake equipment types shall be considered. In such cases, the two brake equipment types shall be identified and accounted for separately in the calculation.

NOTE 2 The total quantity of axles is the result of the sum of the quantity of braked and unbraked axles.

5.2.2 Vehicle and train characteristics

5.2.2.1 Static mass per axle, Static mass

When there are different “static mass per axle”, see 3.1.1, the location in the train shall be indicated.

5.2.2.2 Equivalent rotating masses

Rotating mass (as defined in EN 14478) shall be calculated using a theoretical approach or an approved test method when applicable.

It shall be indicated the wheel size and the relevant static mass condition which is related to the mass inertias (e.g. new wheel and tare load condition).

When there are different “rotating mass per axle”, the location in the train shall be indicated.

5.2.2.3 Wheel diameters

The wheel diameter is measured on the nominated line of contact with the running surface of the rail.

The wheel diameter used in the emergency brake calculation shall be that of a wheel which gives the lowest deceleration (e.g. in the case of disc brakes, this would normally be the maximum wheel diameter).

For checking the adhesion required, τ_{req} , the wheel diameter used shall be that which gives the maximum adhesion required (e.g. in the case of disc brakes, this would normally be the minimum wheel diameter).

If the train is equipped with different sizes of wheels, each size of wheel shall be indicated to the train composition.

5.2.2.4 Train resistance

The value of train resistance may be by analogy to another existing vehicle, or based on a specific calculation.

When the values are the results of tests, the test conditions shall be similar to the expected operating conditions.

The train resistance is represented by a formula which consists of:

a) one term independent of vehicle speed;

b) one term proportional to the speed, dealing with the mechanical components (train and track);

c) a third term proportional to a power n of the speed (aerodynamic resistance).

According to this formula the mathematical formulae that shall be applied are the following:

To obtain the instantaneous train resistance as a function of the speed:

$$F_{Ra} = A + B \cdot v + C \cdot v^{n} \qquad (1)$$

where:

F_{Ra}	is the instantaneous value of the train resistance	N
v	is the instantaneous speed of the vehicle	m/s
A	is the characteristic coefficient of the vehicle	N
B	is the characteristic coefficient of the vehicle.	N/(m/s)
C	is the characteristic coefficient of the vehicle.	$N/(m/s)^n$
n	is the exponent to be defined exactly. In case there is no exact value available, n is estimated to be 2	

For the application of more usual units, the coefficients of the formula shall be adapted.

The above units shall be used for the calculations purpose, but the speed can be expressed usually in km/h and the train resistance in N or kN. In this case, A, B, C are expressed in N, N/(km/h), $N/(km/h)^n$ or kN, kN/(km/h), $kN/(km/h)^n$.

NOTE 1 A, B, and C coefficients are function of various parameters, e.g. mass, train length. Values for A, B, and C may be obtained using the test method given in EN 14067-2.

NOTE 2 For a first calculation, the average train resistance to motion as detailed in EN 14531-1 may be used.

EXAMPLE In all these formulae, the train resistance F_{Ra} is given in N and the instantaneous speed v in m/s.

A = 4 144,9 N;

B = 100,8 N/(m/s);

C = 7,53 N/(m/s²).

For a speed of 300 km/h corresponding to 83,3 m/s, train resistance force is:

F_{Ra} = 4 144,9 + 100,8 × 83,3 + 7,53 × 83,3²;

F_{Ra} = 6 4791 N.

NOTE Other examples of values are given in Annex C.

5.3 Brake equipment characteristics

5.3.1 General

The final result of this part is the braking force generated by each brake equipment related to the top of the rail.

This clause considers the braking force generated by each brake equipment type by reference to the most common brake equipment i.e. tread and disc braking. If this equipment is not applicable, other suitable methods of brake force calculation should be adopted.

5.3.2 Friction brake equipment forces

5.3.2.1 Tread brake unit

The brake equipment of a tread brake unit acts on one shoe arrangement per cylinder as shown in Figures 1 and 2.

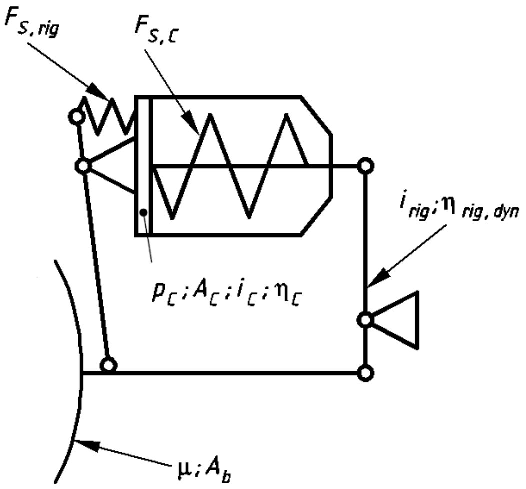


Figure 1 — Pressure applied tread brake unit

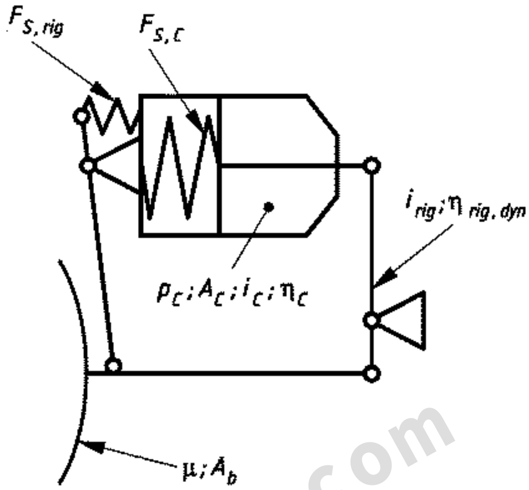


Figure 2 — Spring applied tread brake unit

The braking force characteristic of a tread brake unit can be expressed by:

Output cylinder force

$$F_c = p_c \cdot A_c \cdot i_c \cdot \eta_c + F_{s,c} \quad (2)$$

Application force on the shoe

$$F_n = F_c \cdot i_{rig} \cdot \eta_{rig,dyn} + F_{s,rig} \quad (3)$$

Braking force per unit

$$F_{B,C} = F_n \cdot \mu \quad (4)$$

where:

p_C	is the brake cylinder pressure	Pa
A_C	is the brake cylinder piston area	m^2
η_C	is the cylinder efficiency	-
i_C	is the cylinder ratio	-
	NOTE 1 For pressure applied brake equipment: **positive** value; for spring applied brake equipment: **negative** value.	
$F_{S,C}$	is the cylinder spring force	N
	NOTE 2 For braking force: **positive** value; for releasing force: **negative** value.	

$\eta_{rig,dyn}$	is the rigging efficiency in dynamic condition	-
i_{rig}	is the rigging ratio	-
$F_{S,rig}$	is the rigging spring force	N
	NOTE 3 For braking force: **positive** value; for releasing force: **negative** value.	
μ	is the friction coefficient	-
A_b	is the area of the shoe (appear only in the Figures 1 and 2, not in the above formulae)	m^2

5.3.2.2 Clasp brake

If clasp brakes are utilized, then their relevant and specific brake characteristics shall be applied in accordance with EN 14531-1.

5.3.2.3 Disc brake unit

A disc brake unit typically acts on one caliper per cylinder as shown in Figures 3 and 4.

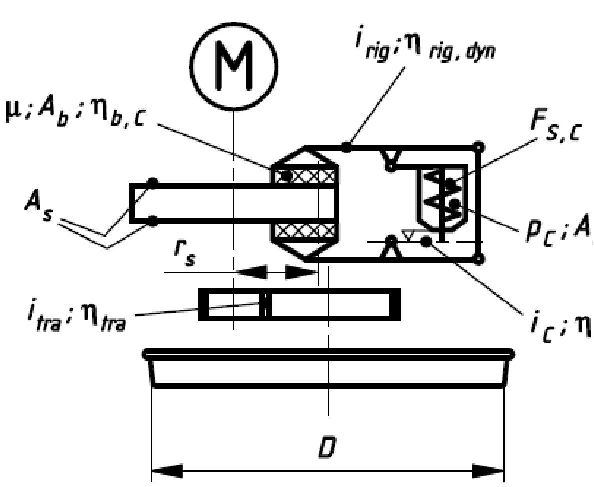


Figure 3 — Pressure applied disc brake unit

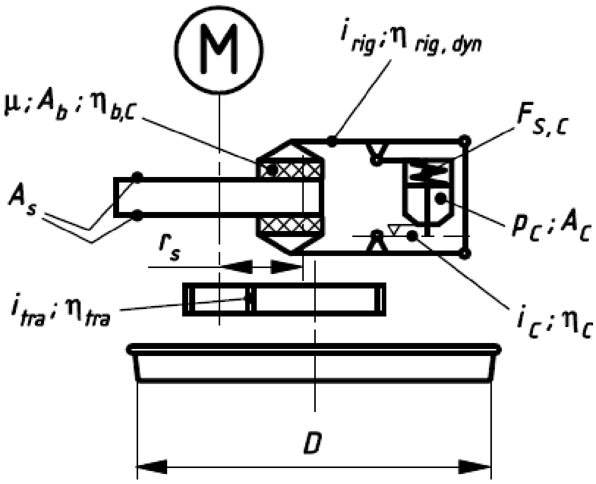


Figure 4 — Spring applied disc brake unit

The braking force characteristic of a disc brake unit can be expressed by:

Output cylinder force

$$F_C = p_C \cdot A_C \cdot i_C \cdot \eta_C + F_{S,C} \qquad (5)$$

Clamp force on the pad

$$F_n = \left(F_C \cdot i_{rig} \cdot \eta_{rig,dyn}\right) / n_{b,C} \qquad (6)$$

Tangential force on the disc

$$F_t = F_n \cdot \mu \cdot n_{b,C} \qquad (7)$$

Braking force per unit

$$F_{B,C} = F_t \cdot \frac{r_s}{D/2} \cdot \frac{i_{tra}}{\eta_{tra}} \quad (8)$$

where:

p_C	is the brake cylinder pressure	Pa
A_C	is the brake cylinder piston area	m^2
η_C	is the cylinder efficiency	-
i_C	is the cylinder ratio	-
	NOTE 1 For pressure applied brake equipment: **positive** value; for spring applied brake equipment: **negative** value.	
$F_{S,C}$	is the cylinder spring force	N
	NOTE 2 For braking force: **positive** value; for releasing force: **negative** value.	
$\eta_{rig,dyn}$	is the rigging efficiency in dynamic condition	-
i_{rig}	is the rigging ratio	-
μ	is the friction coefficient	-
η_{tra}	is the transmission efficiency	-
i_{tra}	is the transmission ratio	-
A_b	is the type and area of the pad per face of disc (appear only in the Figures 3 and 4, not in the above formulae)	m^2
r_s	is the mean swept radius	m
D	is the diameter of the wheel	m
A_s	is the swept area (2 faces) of the disc (appear only in the Figures 3 and 4 , not in the above formulae)	m^2
$n_{b,C}$	is the quantity of pads per cylinder	-

5.3.2.4 Coefficient of friction

The nominal static and dynamic values of the coefficient of friction shall be established using the methods according to prEN 15328.

Because of this large influence, information based upon test results detailing the characteristic of the coefficient of friction of the brake blocks and/or pads shall be provided. As a minimum averaged friction coefficients specific speed ranges which depends on the project shall be provided.

Corresponding test reports (or extracts of these documents) should be attached with the performance calculation.

NOTE Generally, the coefficient of friction value is dependent upon principally five parameters: instantaneous speed, temperature, pressure, humidity, and the energy dissipated. In some cases, it is necessary to take into account other ambient influences (for example corrosive atmosphere). It is impossible to describe precisely the coefficient of friction with all five parameters defined above simultaneously. Generally, according to the friction material of the block or the pad, only two of them, being the most representative of the sensitivity of the materials are chosen. After gaining experience of a particular friction material on specific applications or through bench tests, it is possible to determine an average value of the coefficient of friction dependent on only one or two parameters. Unless otherwise specified, the braking performance should be achieved for the defined climatic conditions.

5.3.2.5 Weighing device signal acting on cylinder pressure

On vehicles, the cylinder pressure may be continuously adapted according to the static mass.

$$p_{\mathrm{C}} = f(m_{\mathrm{st}}) \tag{9}$$

where

p_{C}	is the pressure at the brake cylinder	Pa
m_{st}	is the static mass	kg

5.3.3 Characteristics of the other brake equipment types

5.3.3.1 Electrodynamic brake

Generally, the electrodynamic brake force may be represented by a characteristic curve that is an approximation of first order. This principle is shown in Figure 5.

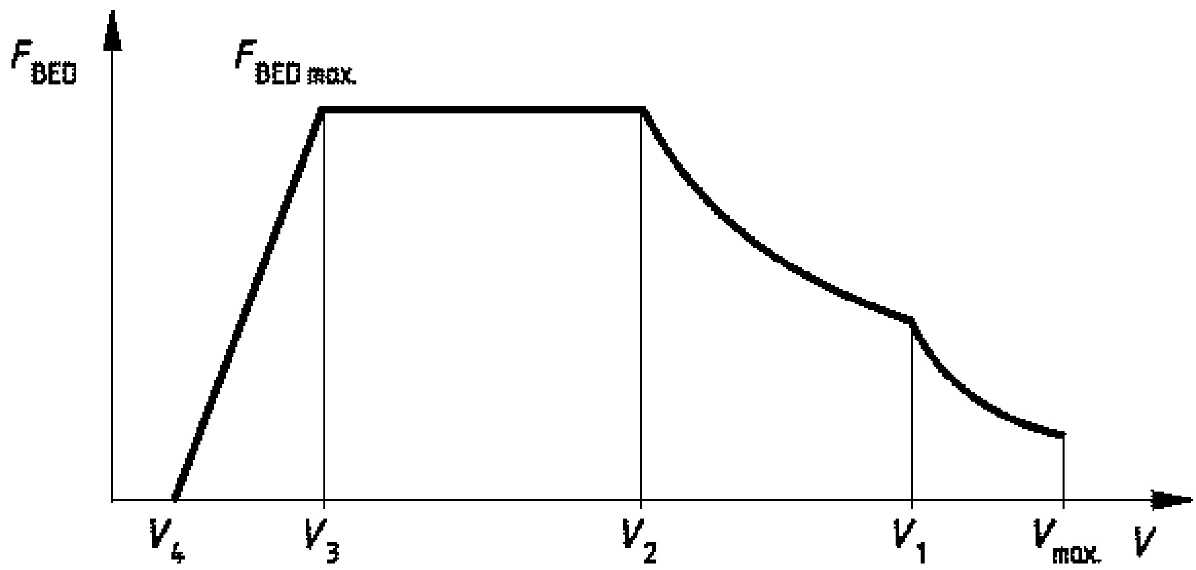


Figure 5 — Characteristic of the electrodynamic brake force

NOTE 1 The indices 1, 2, 3, 4 of the speed v, are given in the sense of the braking process, starting with the initial speed.

NOTE 2 The section of the curve (depending on $1/v^2$) is used with regenerative braking when the voltage has to be limited. When this section is not used, the maximum speed v_{max} equals v_1.

NOTE 3 The electrodynamic brake force can vary as a function of the static mass.

The cuve is composed of:

a linear section from v_4 to v_3 $$F_{BED} = F_{BED,max} \cdot \frac{v - v_4}{v_3 - v_4} \quad (10)$$

a constant section from v_3 to v_2 $$F_{BED} = F_{BED,max} \quad (11)$$

a hyperbolic section with constant power from v_2 to v_1 $$F_{BED} = F_{BED,max} \cdot \frac{v_2}{v} \quad (12)$$

a section depending on 1/ v^2 from v_1 to v_{max} $$F_{BED} = F_{BED,max} \cdot \frac{v_2 \times v_1}{v^2} \quad (13)$$

where:

F_{BED}	is the instantaneous electrodynamic braking force	N
$F_{BED,max}$	is the maximum electrodynamic braking force (= value of the force in the constant section)	N
v	is the instantaneous speed	m/s
v_1.. v_4	are the particular speeds	m/s
v_{max}	is the maximum operational speed	m/s

This curve can also be determined by numerical or practical methods. The values can be given as a table.

5.3.3.2 Fluid retarder

If fluid retarders are utilized, then their relevant and specific brake characteristics shall be applied.

5.3.3.3 Magnetic track brake

Usually, the magnetic track brake force is represented by a curve that gives the instantaneous braking force versus the instantaneous speed. This principle is shown in Figure 6.

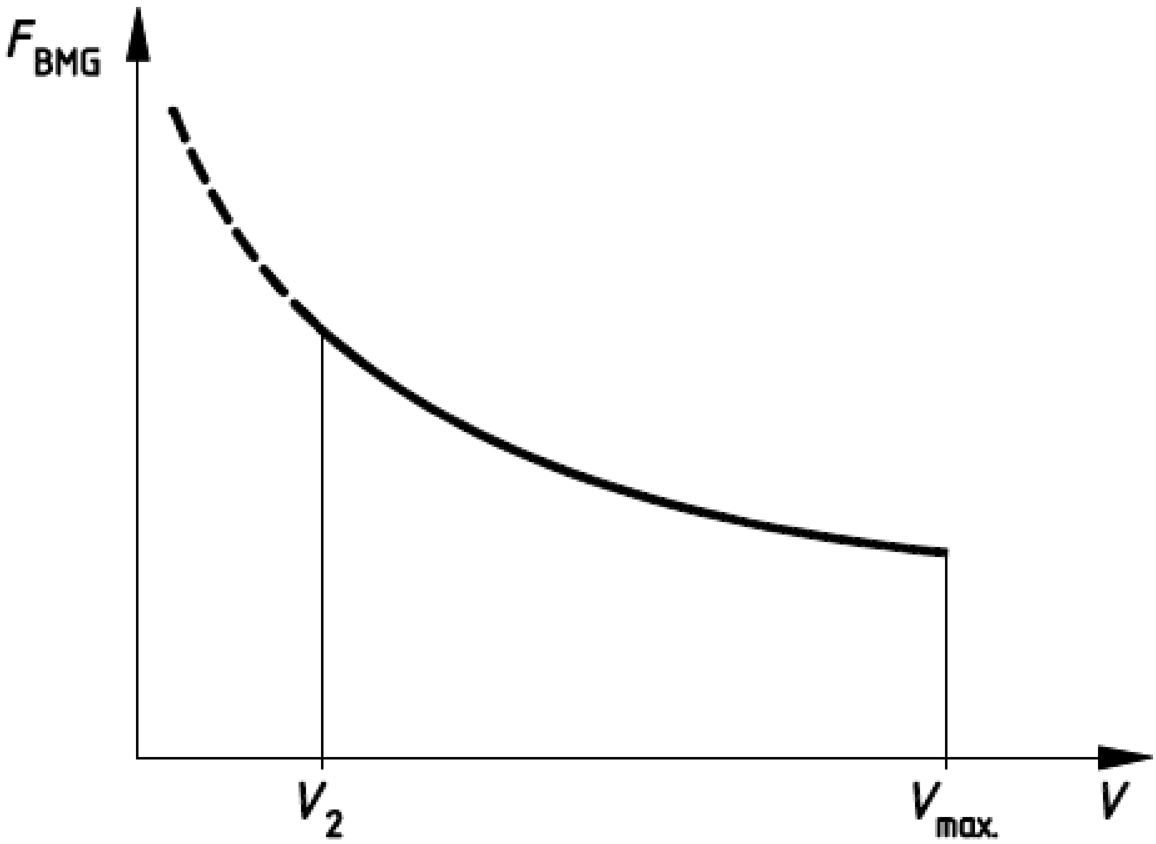


Figure 6 — Characteristics of the magnetic track brake force

The magnetic track brake force can be expressed by:

$$F_{BMG} = F_{AMG} \cdot f_{MG} \tag{14}$$

where:

F_{BMG}	is the instantaneous magnetic braking force	N
F_{AMG}	is the magnetic attraction force (≅ constant)	N
f_{MG}	is the instantaneous coefficient of friction between the magnet and the track	-

A typical characteristic of the instantaneous coefficient of friction may be expressed by the formula

$$f_{MG} = \frac{1}{a_1 \cdot v + a_0} \tag{15}$$

where:

f_{MG}	is the instantaneous coefficient of friction between the magnet and the track	-
v	is the instantaneous speed	m/s
a_0	is a constant coefficient	-

a_1 is a constant coefficient (m/s)$^{-1}$

This curve can also be determined by numerical or practical methods. The values can be given as a table.

5.3.3.4 Eddy current brake

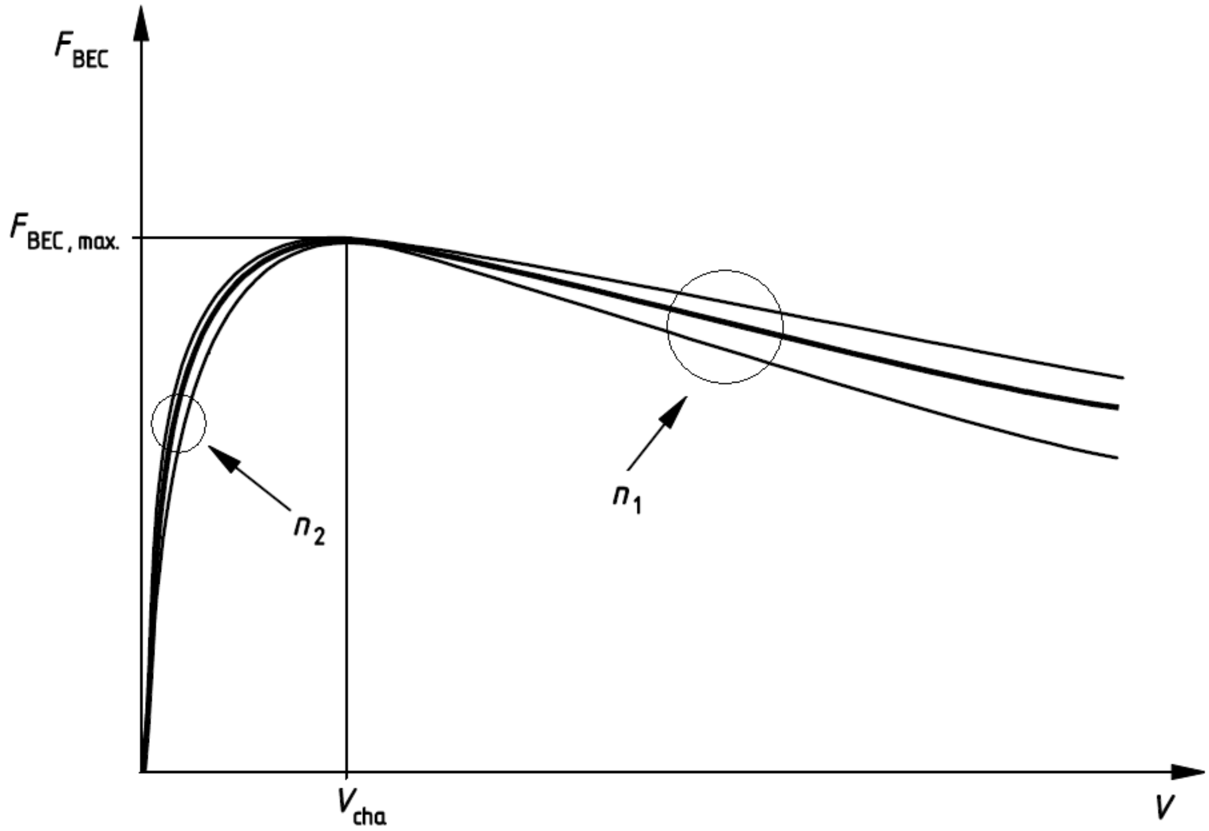


Figure 7 — Characteristics of the eddy current brake force

The eddy current braking force depends on:

a) the gap between the shoe and the track;

b) the instantaneous speed;

c) the intensity of the magnetic field.

Generally, the instantaneous force F_{BEC} can be given by a general specific formula like:

$$F_{BEC} = F_{BEC,max} \cdot \frac{2}{\left(\frac{v}{v_{cha}}\right)^n + \left(\frac{v_{cha}}{v}\right)^n} \quad (16)$$

with:

— $n = n_1$ for $v \geq v_{cha}$

— $n = n_2$ for $v < v_{cha}$

where:

F_{BEC}	is the instantaneous eddy current braking force	N
$F_{BEC,max}$	is the maximum eddy current braking force	N
v	is the instantaneous speed	m/s
v_{cha}	is the characteristic speed where $F_{BEC} = F_{BEC,max}$	m/s
n	is a specific exponent	-

This curve can also be determined by numerical or practical methods. The values can be given as a table.

5.3.4 Time characteristics of each brake equipment type

5.3.4.1 Generation of characteristics

For step-by-step calculation, the time characteristic of a brake equipment type can be simulated by numerical methods or determined by practical methods or by estimations. The values can be given as a table (e.g. see C.1.4.1.2 and C.1.4.2.3).

In the step-by-step calculation, an instantaneous characteristic can be expressed by multiplication of the nominal braking force with a dimensionless factor (see 5.8). As example, the braking response of a brake equipment can be considered with such dimensionless factor as a characteristic depending on time.

5.3.4.2 Creation of input data

The values generated according to 5.3.4.1 can be used directly or converted to a practical approximation, e.g. a linear description (see C.1.4.1.2 and C.1.4.2.3).

The plausibility calculation can be eased applying simple approximations of the time behaviour. See Annex B.

NOTE 1 Usually, the time characteristic is considered for each brake equipment when the brake force of this equipment becomes greater than zero.

NOTE 2 For any change of brake force during one established braking cycle, the time characteristics for the change of force of each brake equipment type is not considered.

NOTE 3 In this standard the slowing calculation generally does not consider release characteristics. For special calculations, the use of release characteristics is permitted.

5.3.4.3 Delay time (t_a or t_c)

Period of time commencing when a change (positive or negative) in brake demand is initiated and ending when achieving *a%* or *c%* of the established braking force of the brake equipment (see Figures 8 and 9).

5.3.4.4 Build-up time (t_{ab}) / Release time (t_{cd})

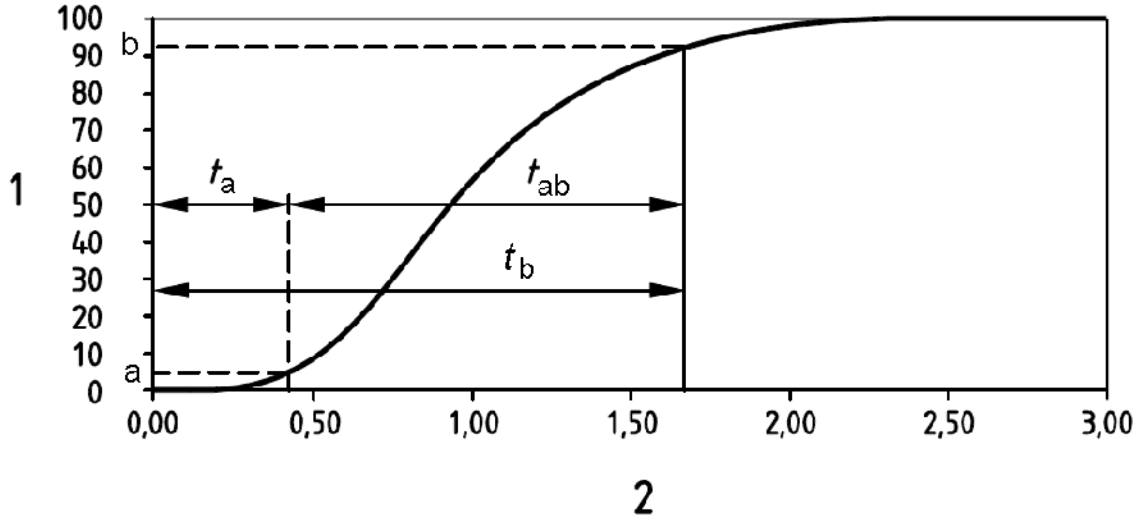
Period of time commencing at the end of the delay time and ending when achieving *b%* or *d*% of the established braking force of the brake equipment (see Figures 8 and 9).

5.3.4.5 Response time (t_b or t_d)

Period of time commencing when a change (positive or negative) in brake demand is initiated and ending when achieving *b% or d%* of the established braking force of the brake equipment.

It can be calculated using the following equations (see Figures 8 and 9):

$$t_b = t_a + t_{ab} \tag{17}$$

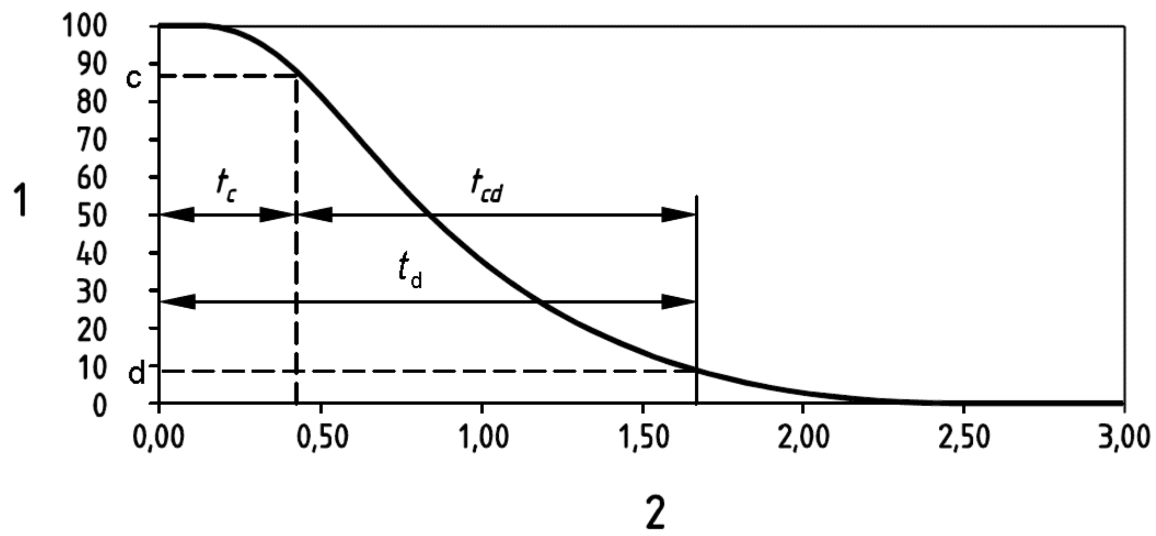


Key

1	factor of nominal braking force or deceleration in %
2	time in s
t_a	delay time
t_{ab}	brake build-up time
a	is employed for the commencement of braking
b	is employed when the build-up of braking force has been achieved

Figure 8 — Delay and build-up time for brake application

$$t_d = t_c + t_{cd} \tag{18}$$



Key

1	factor of nominal braking force or deceleration in %
2	time in s
t_c	delay time
t_{cd}	brake release time
c	is employed for the commencement of release
d	is employed when the brake release has been substantially achieved

Figure 9 — Delay and release time for brake release

5.3.5 Blending rules

Blending rules are required when it is intended to use several types of brakes together:

a) adhesion dependent/adhesion independent brakes;

b) using friction brakes or not using friction brakes.

The target is to maximize the use of those brakes that do not wear (the electrodynamic brakes, etc.) and minimize the use of the friction brake (which is subject to wear) within the boundaries specified for the safety and integrity of the total brake system.

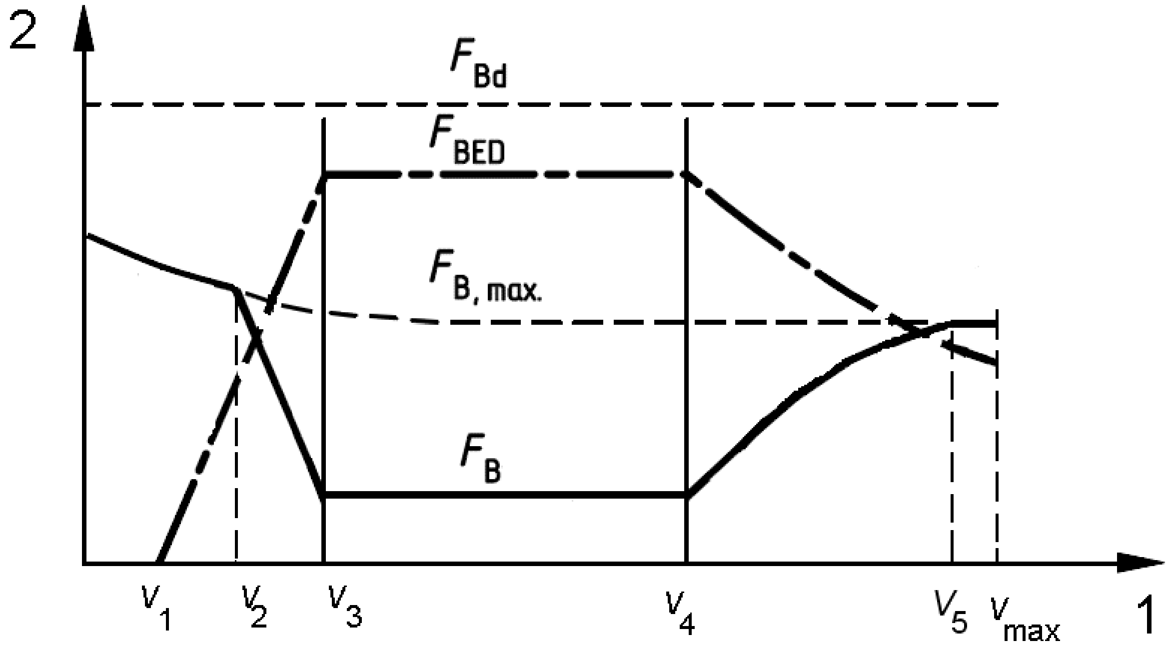
The blending rules permit sharing of the brake demand between the different types of brakes in such a way that the total brake demand is achieved.

The total brake force on an axle (bogie) is limited by a typical value depending on the adhesion, e.g. see the limits stated in the TSI rules. This value shall be stated in the design specification if it differs from the TSI rules.

The actual demand can be expressed by a typical curve or other set of data.

There is not a general blending rule. Blending rules in normal mode and degraded modes (see 5.4.6) shall be designed specifically for each project. The general blending formula shall be applied, depending on the project, to one axle, one bogie, one vehicle, some vehicles controlled together or a complete train.

EXAMPLE Typical projects with blending rules e.g. between the electrodynamic brake and the friction brake can be formulated as functions of speed, energy, temperatures, etc.



Key

v	instantaneous speed
$v_2 \dots v_4$	particular speeds
v_{max}	maximum operational speed
1	axis of speed (in m/s)
2	axis of braking force (in N)

Figure 10 — Example of a blending rule between the electrodynamic brake and the friction brake versus speed

$$F_B = \min\left(F_{B,max}; \left(F_{Bd} - F_{BED}\right)\right) \tag{19}$$

where:

F_B	is the instantaneous friction brake force	N
$F_{B,max}$	is the maximum friction brake force available	N
F_{Bd}	is the brake force demand	N
F_{BED}	is the instantaneous electrodynamic braking force	N

5.4 Initial and operating characteristics

5.4.1 Mean gradient of the track

In general, design calculations and Wheel Slide Protection tests are based on the assumption of a horizontal track.

NOTE A constant inclination of the track throughout the stopping or slowing distance is assumed.

Otherwise the gradient is defined with:

$$i = \tan\alpha \tag{20}$$

with α angle of inclination.

For calculation of external forces that result from gradients in railway applications the following simplification is commonly used:

$$\sin\alpha \approx \tan\alpha \text{ and} \quad (21)$$

$$\cos\alpha \approx 1 \quad (22)$$

This simplification creates an error of about 1 % at a gradient i = 0,08. It is mandatory to use the exact definition if higher gradients are specified.

$$\sin\alpha = \frac{i}{\sqrt{i^2 + 1}}$$

(23)

and

$$\cos\alpha = \frac{1}{\sqrt{i^2 + 1}}$$

The effect of the gradient is:

$$F_g = \frac{m_{st} \cdot g_n \cdot i}{\sqrt{i^2 + 1}} \quad (24)$$

where

F_g	is the downhill force on the train	N
m_{st}	is the static mass of the train	kg
g_n	is the standard acceleration of free fall	m/s^2
i	is the gradient (rising gradient is positive)	-

5.4.2 Initial speed

For design and unless otherwise specified, the calculations are performed with different initial speeds.

5.4.3 Available coefficient of adhesion

For calculations it is generally assumed that there is no limitation given by the coefficient of adhesion (unless otherwise specified).

It shall nevertheless be checked that the required adhesion of each axle calculated according to 5.12.6 stays lower than the available adhesion. This available coefficient of adhesion is depending on the conditions of the braking (sanding, speed, environmental conditions, length of the vehicle, etc.).

If the required adhesion exceeds the available one, it can lead to an increase of the stopping distance related to the theoretical calculation because of a locking of the wheel or regulation by the wheel slide protection device.

5.4.4 Level of the brake demand

Generally, only the emergency brake demand is considered during calculations (unless otherwise specified).

Other brake demand levels may be considered when establishing the design of each braking equipment.

5.4.5 Quantity of each brake equipment type available

Calculations shall be performed with all the brake equipment in working order and with a specified quantity / location of isolated brakes.

5.4.6 Calculation in degraded conditions

Generally, brake calculations are performed with nominal parameters of the brake equipment in use. It is recommended to consider degraded mode conditions affecting the performances of the brakes, like friction coefficient, available coefficient of adhesion, or isolated equipments.

See the relevant standards and operator specifications.

5.5 Sharing, proportioning of the brake forces - achieved forces

The achieved forces are the forces that are calculated when blending rules are used (5.3.5). They may be lower than the maximum forces.

NOTE The blending rules can have an influence either on the train (motor and trailer axles) or only on some bogies (motor axles).

5.6 Braking force per axle

The braking force per axle is the summation of the forces provided by all the brake equipment acting on that axle.

5.7 Total force on train level

5.7.1 External force

This is the addition of the effect of the mean gradient (see 5.4.1) and specified environmental effects.

If specified, the effect of external wind force shall be taken into account.

NOTE The formula to be used depends upon the application.

5.7.2 Total retarding force

This is the summation of the braking forces provided by:

the brakes,

the train resistance to motion, and

the external forces (see 5.7.1).

5.8 Time step integration loop

By convention, deceleration and retarding force are considered positive values.

The initial step begins at time t_0 = 0 s simultaneous with the braking demand.

The time step Δt selected for the calculation shall be determined according to the relative distance deviation Δs of the calculation, (i.e. this relative distance deviation obtained from the distance calculations with time steps Δt and (2 x Δt) shall not be greater than the minimum precision required). If not otherwise specified (e.g. by another European Requirement), the value of deviation must be Δs = 0,001.

The value of the relative distance deviation is given by the following formula.

$$\Delta s = \left| \frac{s_{f(2\cdot\Delta t)} - s_{f(\Delta t)}}{s_{f(\Delta t)}} \right| \tag{25}$$

where:

Δt	is the time step of integration loop	s
$s_{f(\Delta t)}$	is the distance, calculated with time step Δt	m
$s_{f(2\cdot\Delta t)}$	is the distance, calculated with doubled time step $(2 \times \Delta t)$	m
Δs	is the relative distance deviation	

An example of method is explained in Annex B**.**

In the step-by-step calculation, an instantaneous characteristic, e.g. characteristic depending on time, speed, etc., can be expressed by multiplication of a dimensionless factor as a function of time, speed, etc, e.g. time characteristic of the friction brake.

$$F_{\mathrm{B}} = F_{\mathrm{B,n}} \cdot f(t) \cdot f(v) \cdot \ldots\ldots \cdot f(x) \tag{26}$$

where:

F_{B}	is the current brake force	N
$F_{\mathrm{B,n}}$	is the nominal brake force	N
$f(x)$	is a dimensionless factor (common characteristic) If the force is independent of a characteristic x, $f(x)$ = 1 (100 %)	-;%
t	is the current point of time	s
v	is the current speed	m/s

5.9 Other decelerations

5.9.1 General

By convention, deceleration is considered a positive value.

5.9.2 Decelerations supplied by each braking force (a_i)

The deceleration supplied by each brake type, i, a_i, is calculated from the equation as follows.

$$a_i = \frac{F_{B,i}}{m_{dyn}} \quad (27)$$

where

a_i	is the deceleration supplied by the brake type i	m/s^2
$F_{B,i}$	is the braking force of brake type i	N
m_{dyn}	is the dynamic mass of the train ($= m_{st} + m_{rot}$)	kg

5.9.3 Equivalent deceleration (a_e)

The equivalent deceleration is equal to a mean deceleration with respect to the distance during braking over a specific speed range. The deceleration a_e is based on a calculation with a fully applied brake force.

$$a_e = \frac{1}{(s_2 - s_0)_{f(t)=100\%}} \cdot \int_{s_0}^{s_2} a_{f(t)=100\%}\, ds = \frac{{v_0}^2 - {v_2}^2}{2 \cdot (s_2 - s_0)_{f(t)=100\%}} \quad (28)$$

where

s_0	is the initial distance	m
s_2	is the final distance	m
$(s_2 - s_0)_{f(t)=100\%}$	is the braking distance without consideration of any response characteristics	m
$a_{f(t)}$	is the deceleration during each chosen time step	m/s²
ds	is the distance difference during each chosen time step	m
v_0	is the initial speed	m/s
v_2	is the final speed	m/s
$f(t) = 100\ \%$	is the index stands for 100 % applied braking force without consideration of any response characteristics	-

NOTE As an example for mass transit, see also EN 13452-1 and EN 13452-2.

5.10 Time

5.10.1 Slowing time (t)

The slowing time is defined as the time difference beginning with the initial brake demand and ending by achieving the final speed v_2. The slowing time is obtained by conducting the time step calculation (see 5.8).

5.10.2 Stopping time (*t*)

The stopping time is defined as the time difference beginning with the initial brake demand and ending by achieving the final speed v_2.= 0 m/s. The stopping time is obtained by conducting the time step calculation (see 5.8).

5.10.3 Equivalent response time (t_e)

The equivalent response time is an auxiliary quantity in a simplified computing model. This model is based on the assumption that braking consists of a gradient-independent, unbraked rolling phase and a deceleration process. The equivalent response time corresponds to the duration of the rolling phase.

Two time integrations shall be performed to compute this quantity:

in a first step, the braking distance *s* taking into account the time behaviour of all systems involved in the braking process is computed;

then the braking distance $s_{f(t)=100\%}$ without taking into account the time behaviours is computed, i.e. all time behaviours are set to $f(t)$ = 100 %.

The equivalent response time is a result of:

$$t_{\mathrm{e}} = \frac{s - s_{f(t)=100\%}}{v_0} \tag{29}$$

It is assumed that the calculated equivalent response time t_{e} is a collective system response time applicable to the whole train.

NOTE In the case of a classical braking system, e.g. emergency braking with friction only, the equivalent time of application can be simplified by using the sum of the delay period and half of the brake force build up time, where the build up time is defined as the time needed to reach 95 % of the braking force demanded for the first braking step.

5.11 Distance calculations

5.11.1 General

The calculated stopping or slowing distance s is obtained by conducting the time step calculation (see 5.8).

NOTE The following distance calculations are only used for simplified descriptions of braking characteristics.

5.11.2 Slowing distance (*s*)

The slowing distance is defined as the distance run between the initial brake demand and the end by achieving the final speed v_2. The calculated slowing distance is obtained by conducting the time step calculation (see 5.8).

5.11.3 Stopping distance (*s*)

The stopping distance is defined as the distance run between the initial brake demand and standstill. Basically, the stopping distance is a direct result of the time step calculation (see 5.8).

5.11.4 Equivalent free run distance *(s_0)*

The equivalent free run distance s_0 is a theoretical distance without deceleration or acceleration. It is calculated using the following equation:

$$s_0 = v_0 \cdot t_e \tag{30}$$

where:

s_0	is the equivalent free run distance	m
t_e	is the equivalent response time	s
v_0	is the initial speed	m/s

5.12 Other calculations

5.12.1 Total energy (W_{tot})

The “Total energy” is the sum of the dissipated energy of all applied brake equipment types and train resistance which is equal to the related difference of kinetic and potential energy. It is given by:

$$W_{tot} = \frac{m_{dyn} \cdot (v_0^2 - v_2^2)}{2} - {}_{st} \cdot g_n \cdot s \cdot \frac{i}{\sqrt{i^2 + 1}} = W_B + W_{Ra} \tag{31}$$

where:

W_{tot}	is the total energy	J
W_B	is the energy dissipated by the brake systems	J
R_a	is the energy dissipated by the train resistance	J
g_n	is the standard acceleration of free fall	m/s^2
i	is the gradient	-
m_{dyn}	is the dynamic mass of the train	kg
st	is the static mass of the train	kg
v_0	is the initial speed	m/s
v_2	is the final speed	m/s
s	is the distance between v_0 and v_2	m

5.12.2 Energy dissipated by each type of brake

The energy dissipated by each type of brake shall be calculated as follows:

$$W_{B,i} = \int_{s_0}^{s_2} F_{B,i}(s) \cdot ds \tag{32}$$

For constant braking forces, the following equation can be used:

$$W_{B,i} = F_{B,i} \cdot s_B \tag{33}$$

where:

$W_{B,i}$	is the energy dissipated by brake system i	J
$F_{B,i}$	is the braking force i	N
s_0	is the initial distance	
s_2	is the final distance	
s_B	is the braking distance; $s_B = s_2 - s_0$	m
ds	is the distance difference during each chosen time step	m

5.12.3 Energy per unit friction area dissipated by each type of friction brake

The energy per unit friction area dissipated by each type of friction brake shall be calculated as follows:

$$W_{S,i} = \frac{W_{B,i}}{A_{s,i}} \tag{34}$$

where:

$W_{S,i}$	is the energy dissipated by friction brake type i per unit area	J/m^2
$W_{B,i}$	is the energy dissipated by friction brake type i	J
$A_{s,i}$	is the swept area of the friction surface of the disc i or the wheel tread i	m^2

5.12.4 Maximum power for each type of brake

The maximum power for each type of brake shall be calculated as follows:

$$P_{max,i} = \max\left(F_{B,i} \cdot v\right) \tag{35}$$

In case of constant braking force during the braking, maximum power is equal to:

$$P_{max,i} = F_{B,i} \cdot v_0 \tag{36}$$

where:

$P_{max,i}$	is the maximum power of brake type i	W
$F_{B,i}$	is the braking force of brake type i	N
v	is the speed	m/s
v_0	is the initial speed	m/s

5.12.5 Maximum specific power flux for each type of friction brake

The maximum specific power flux for each type of friction brake shall be calculated as follows:

$$P_{\mathrm{S,max},i} = \frac{P_{\mathrm{max,i}}}{A_{\mathrm{s,i}}} \qquad (37)$$

where:

$P_{\mathrm{S,max,i}}$	is the maximum power flux of friction brake system i	W/m²
$P_{\mathrm{max,i}}$	is the maximum power of friction brake system i	W
$A_{\mathrm{s,i}}$	is the swept area of the friction surface of the disc i or the wheel tread i	m^2

5.12.6 Required adhesion value for each type of axle ($\tau_{req,ax}$)

The required adhesion value for each type of axle shall be calculated as follows:

$$\tau_{req,ax} = \frac{\left(\sum_{ax} F_{B,i} - m_{rot,ax} \cdot a\right)}{m_{st,ax} \cdot g_n} \cdot \sqrt{1+i^2} \qquad (38)$$

where:

$\tau_{\mathrm{req,ax}}$	is the required adhesion value for the axle	-
$\sum_{ax}$	is the sum of all involved adhesion requiring brake types per axle	
$F_{\mathrm{B,i}}$	is the braking force of brake system i	N
a	is the instantaneous deceleration of the vehicle	m/s^2
g_{n}	is the standard acceleration of free fall	m/s
i	is the gradient	-
$m_{\mathrm{rot,ax}}$	is the rotational mass of the axle	kg
$m_{\mathrm{st,ax}}$	is the static mass acting on the axle	kg

6 Immobilization brake calculation

6.1 General

The immobilization brake is used to prevent a stationary train from moving i.e. holding and parking braking in accordance with EN 14478.

The parking braking is generally provided by specific brake equipment types. The holding braking can be applied with different brake equipment types (see 5.3).

Characteristics considered for immobilization brake calculation can differ e.g. static coefficient of pad and block friction (see 6.3.1).

6.2 General characteristics

The parameters to define immobilization configuration are:

a) quantity of axles;

b) quantity of braked axles for each adhesion dependent brake equipment type;

c) quantity of non-adhesion dependent brake equipment type.

Each brake equipment type shall be the subject of a specific calculation.

All of the various types of brake equipment applied to one axle shall be highlighted and respected.

NOTE When there are several brake equipment types, it is preferable to identify each type (for example by means of a number: type 1, type 2, etc.).

Immobilization calculations consider the static mass per axle (see 3.1.1).

6.3 Characteristics of the immobilization brake equipment

6.3.1 Coefficient of friction of the pads and blocks

The coefficient of friction is the main characteristic of friction brake equipment types to be taken into account in the immobilization brake performance.

The nominal static and dynamic values of the coefficient of friction shall be established using the methods according to prEN 15328.

Unless otherwise specified, the minimum static coefficient of friction determined according to prEN 15328 shall be used.

NOTE Generally, the immobilization follows a stopping braking and in this case the blocks and pads are often very hot. Then, their friction coefficient is greatly influenced by the heat and the expected value is lower than usual.

6.3.2 Characteristics of a permanent magnetic track brake

In the case of permanent magnetic track brake acting as a parking brake, see EN 14531-1.

6.3.3 Characteristics of other immobilization brakes

In the case of other brakes acting as a parking brake, see EN 14531-1.

6.4 Train and operating characteristics

The immobilization shall be calculated for the following specific conditions:

a) gradient;

b) load;

c) wheel diameter (see 5.2.2.3);

d) wind;

e) isolated brake equipment;

f) available adhesion conditions (see 6.2).

6.5 Immobilization force provided by each equipment type

6.5.1 Force of a disc brake unit

In the case of spring parking brake, it can be acceptable to use directly a minimum guaranteed fixed value either for the cylinder output force or the clamp force. When using these fixed values the calculation follows the definitions of Clause 5.3.2.3.

6.5.2 Force of a tread brake unit

In the case of spring parking brake, it can be acceptable to use directly a minimum guarantied fixed value either for the cylinder output force or the application force. When using these fixed values, the calculation follows the definitions of Clause 5.3.2.1.

6.5.3 Force of a permanent magnetic track brake

In the case of a permanent magnetic track brake acting as a parking brake, the requirements of EN 14531-1 shall apply.

6.5.4 Force of other immobilization brakes

In the case of other brakes acting as a parking brake, the requirements of EN 14531-1 shall apply.

6.6 Immobilization force

6.6.1 Immobilization force per axle

The immobilization force per axle is the summation of the immobilization forces acting on that axle.

$$F_{im,ax} = \left(\sum_i F_{im,i} \right)_{ax} \qquad (39)$$

where:

$F_{\mathrm{im,ax}}$	is the total immobilization force per axle	N
$F_{\mathrm{im,\,i}}$	is the immobilization force of parking brake *i*	N
$\sum_i$	is the summation of all immobilization forces of parking brake *i*	

6.6.2 Total immobilization force

The immobilization force of the train is the summation of the immobilization forces of all axles ax of the train. These immobilization forces are possibly limited by the available adhesion. Therefore the minimum shall be used, either the adhesion transmittable force or the brake applied force.

In case of adhesion independent immobilization brakes, the immobilization force shall be calculated according to EN 14531-1.

$$F_{im} = \sum_{ax} \min\left(F_{im,ax}; \tau_a \cdot m_{st,ax} \cdot g_n \cdot \cos\alpha\right) \qquad (40)$$

where:

$\sum_{ax}$	is the summation of all involved adhesion requiring systems per axle,	
F_{im}	is the total immobilization force of the train	N
$F_{\text{im, ax}}$	is the total immobilization force per axle	N
g_n	is the standard acceleration of free fall	m/s^2
$m_{\text{st,ax}}$	is the static mass per axle	kg
τ_{a}	is the available adhesion	-
α	is the angle of inclination (see 5.4.1)	rad

6.7 External forces

6.7.1 Gradient

The downhill force on the train is defined with:

$$F_{\text{g}} = m_{\text{st}} \cdot g_{\text{n}} \cdot \sin\alpha \tag{41}$$

where:

F_{g}	is the downhill force on the train	N
m_{st}	is the static mass of the train	kg
g_{n}	is the standard acceleration of free fall	m/s^2
α	is the angle of inclination (see 5.4.1)	rad

6.7.2 Wind force on the train

This force can be approximated using the term "C" of the train resistance formula (see 5.2.2.4).

In this case, the wind force on the train is corrected to take into account the direction of the wind that gives the maximum force.

Generally, the wind force is directly specified if the designer has to take it into account:

$$F_{\text{wind}} = D \cdot C \cdot v_{\text{wind}}^{2} \tag{42}$$

where:

F_{wind}	is the wind force on the train	N
D	is the specific value due to the direction of the wind	-
C	is the characteristic coefficient of the aerodynamic train resistance	N/(m/s)^2

v_{wind}	is the speed of the wind	m/s

6.7.3 Train resistance

This force corresponds approximately to the term "A" of the train resistance formula (see 5.2.2.4), considering the train at standstill. It may be used when the wind force of the train is taken into consideration.

$$F_{Ra,im} = A \tag{43}$$

where:

$F_{Ra,im}$	is the train resistance	N
A	is the characteristic coefficient of the train resistance	N

6.8 Final results

6.8.1 Immobilization safety factor

It is the quotient of the immobilization force on the complete train by the forces that would accelerate the train:

$$S_{im} = (F_{im} + F_{Ra\ im}) / (F_g + F_{wind}) \tag{44}$$

where

S_{im}	is the immobilization safety factor	-
F_{im}	is the immobilization force of the train	N
F_g	is the downhill force on the train	N
F_{wind}	is the wind force on the train	N
$F_{Ra,im}$	is the train resistance	N

The immobilization safety factor (S_{im}) shall be greater than 1.

It is possible that a higher safety factor could be required and such factors might take into account failures and/or degraded modes.

NOTE Equation 44 considers the worst combination of the acting forces.

6.8.2 Coefficient of adhesion required by each braked axle

The coefficient of adhesion required by each axle is the quotient of the immobilisation force of the axle and the axle load depending on the existing gradient. This calculation is needed to check if the installed brake force distribution is sufficient regarding available adhesion (slipping limits).

$$\tau_{req,ax} = \frac{F_{im,ax}}{m_{st,ax} \cdot g_n \Big/ \sqrt{i^2 + 1}} \tag{45}$$

For simplification according to 6.7.1, the following equation may be used:

$$\tau_{\text{req,ax}} = \frac{F_{\text{im,ax}}}{m_{\text{st,ax}} \cdot g_{\text{n}}} \tag{46}$$

where:

$\tau_{\text{req,ax}}$	is the coefficient of adhesion required by each braked axle	-
$F_{\text{im,ax}}$	is the immobilization force provided to the axle	N
$m_{\text{st,ax}}$	is the static mass per axle	kg
g_{n}	is the standard acceleration of free fall	m/s^2
i	is the gradient	

NOTE This adhesion calculation is common engineering practice and an often used approximation.

6.8.3 Maximum achievable gradient

The maximum achievable gradient is a balance result of the immobilisation force, resistance force, wind force, and downhill force. This calculation is needed to check if the installed brake force is sufficient regarding the project specific requirements.

$$i_{\text{max}} = \frac{1}{\sqrt{\left(\frac{m_{\text{st}} \cdot g_{\text{n}}}{F_{\text{im}} + F_{\text{Ra,im}} - F_{\text{wind}}}\right)^2 - 1}} \tag{47}$$

For simplification according to 6.7.1, the following equation may be used:

$$i_{\text{max}} = \frac{F_{\text{im}} - F_{\text{wind}} + F_{\text{Ra,im}}}{m_{\text{st}} \cdot g_{\text{n}}} \tag{48}$$

where:

i_{max}	is the maximum achievable gradient	-
F_{im}	is the immobilization force of the train	N
$F_{\text{Ra,im}}$	is the train resistance	N
F_{wind}	is the wind force on the train	N
m_{st}	is the static mass	kg
g_{n}	is the standard acceleration of free fall	m/s^2

NOTE The maximum gradient permitted is normally calculated without taking into account the effects of the wind and the train resistance.

Annex A
(normative)

Workflow of kinetic and static calculations

Table A.1 — Initial data for a stopping and slowing distance calculation

Type of data	Special characteristics	
5.2 General characteristics	5.2.1 Train formation	- Quantity of motor axles - Quantity of trailer axles - Quantity of braked axles for each adhesion dependent brake equipment type - Quantity of non-adhesion dependent brake equipment type
	5.2.2 Vehicle and train characteristics	5.2.2.1 Static mass per axle, Static mass
		5.2.2.2 Equivalent rotating masses
		5.2.2.3 Wheel diameters
		5.2.2.4 Train resistance
5.3 Brake equipment characteristics	5.3.2 Friction brake equipment forces	5.3.2.1 Tread brake unit
		5.3.2.3 Disc brake unit
		5.3.2.4 Coefficient of friction
		5.3.2.5 Weighing device signal acting on cylinder pressure
	5.3.3 Characteristics of the other brake equipment types	5.3.3.1 Electrodynamic brake
		5.3.3.2 Fluid retarder
		5.3.3.3 Magnetic track brake
		5.3.3.4 Eddy current brake
	5.3.4 Time characteristics of each brake equipment type	
	5.3.5 Blending rules	Normal, degraded modes, etc.
5.4 Initial and operating characteristics	5.4.1 Mean gradient of the track	
	5.4.2 Initial speed	
	5.4.3 Available coefficient of adhesion	
	5.4.4 Level of the brake demand	
	5.4.5 Quantity of each brake equipment type available	
	5.4.6 Calculation in degraded conditions	

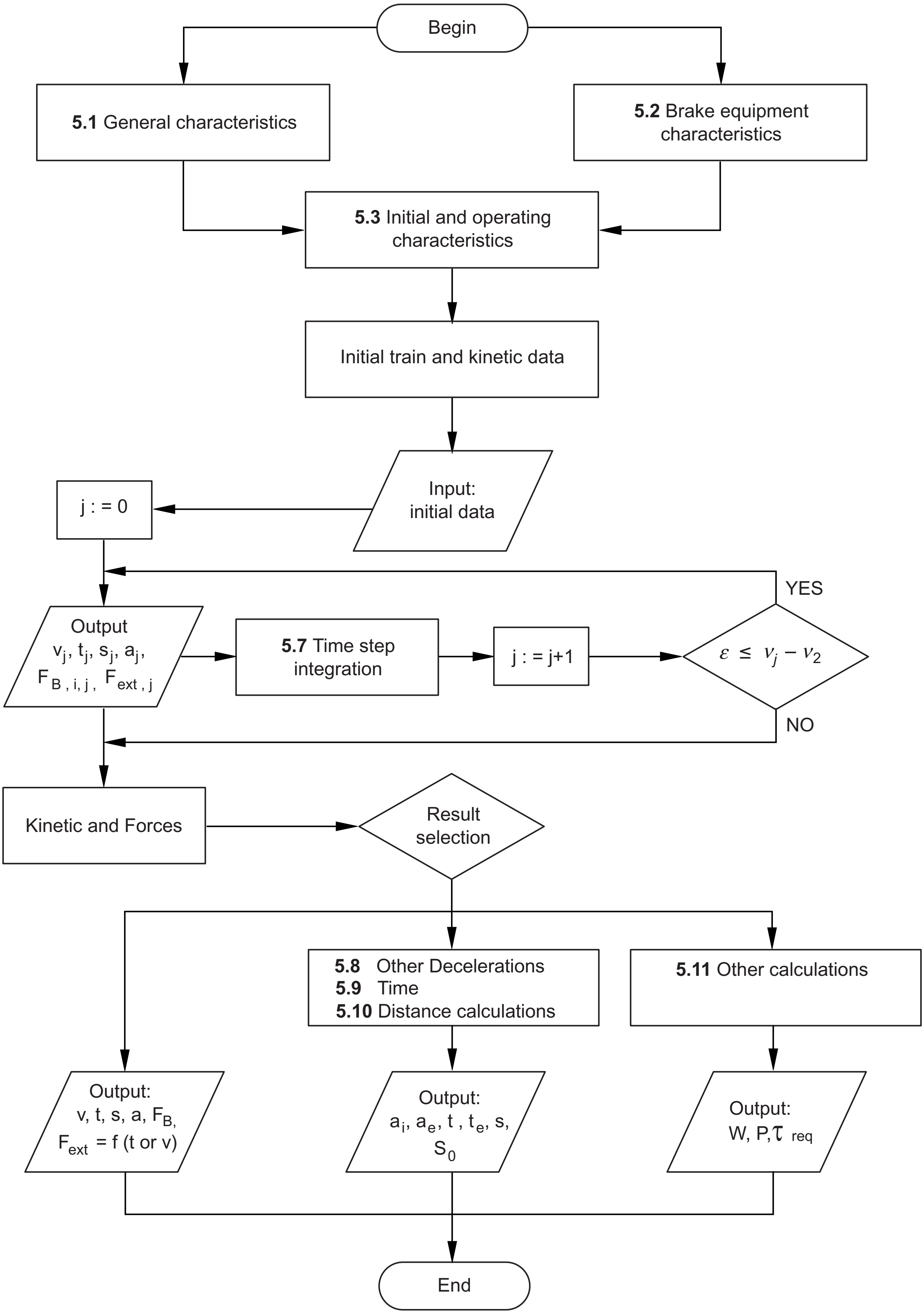


Figure A.1 — Calculation flow diagram for stopping and slowing

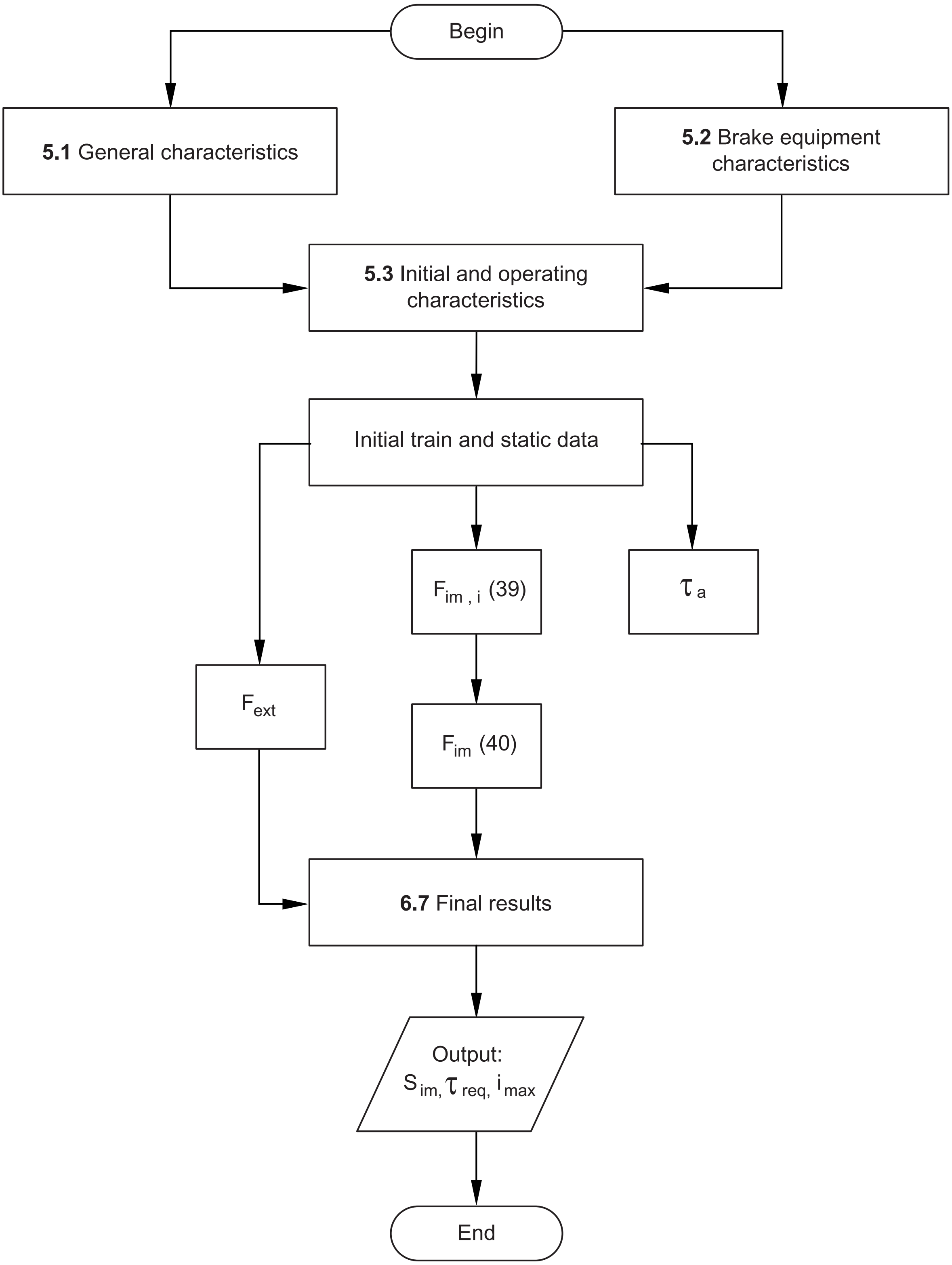


Figure A.2 — Calculation flow diagram for immobilization braking

Annex B
(informative)

Example of time step integration loop

Step 1: Deceleration at step t_j

$$a_j = \frac{\left(\sum F_{B,i} + \sum F_{ext}\right)_j}{m_{dyn}} \quad (49)$$

Step 2: Speed at step t_{j+1}

$$v_{j+1} = v_j - a_j \cdot \Delta t \quad (50)$$

Step 3: Distance at step t_{j+1}

$$s_{j+1} = s_j + v_j \cdot \Delta t - \tfrac{1}{2} \cdot a_j \cdot \Delta t^2 \quad (51)$$

Step 4: Deceleration at step t_{j+1}

$$a_{j+1} = \frac{\left(\sum F_{B,i} + \sum F_{ext}\right)_{j+1}}{m_{dyn}} \quad (52)$$

Step 5: Stop criterion of calculation loop if $\varepsilon \geq v_2 - v_{j+1}$ end step calculation

NOTE 1 For the final step, the criteria is calculated speed less than final speed.

NOTE 2 For the final step, the time step can be adjusted. It becomes a “result” of the calculation.

Step 6: Next time step

$$j = j + 1 \quad (53)$$

$$t_{j+1} = t_j + \Delta t \quad (54)$$

where:

a_j	is the vehicle deceleration at time t_j	m/s^2
ε	is the acceptable deviation from v_2	m/s
$F_{B,i}$	is the braking force of brake type i as function of $f(t,v,s)$	N
F_{ext}	is the external force (for decelerating force **positive** value, for accelerating force **negative** value)	N
j	is the number of integration step	-
m_{dyn}	is the dynamic mass (= $m_{st,}$ + m_{rot})	kg
s_j	is the distance at time t_j	m
Δt	is the time step	s
t_j	is the slowing time at integration step j	s
v_j	is the vehicle speed at time t_j	m/s
v_2	is the final vehicle speed	m/s

Annex C
(informative)

Example of distance and other dynamic calculations

C.1 Input data

Following abbreviations are used in this Annex:

- TA Trailer Axle
- MA Motor Axle
- ED Electrodynamic Brake
- DB Disc Brake
- RES Train resistance

When the columns are grey in the following tables, it means that they are not concerned for the calculations.

C.1.1 Mass data

See 5.2.2.1 to 5.2.2.2.

Table C.1 — Train mass distribution

Designation	Train mass distribution
$m_{st,}/m_{rot}$ t	206/10,8

Table C.2 — Car mass distribution

Designation	**1x Car1**	**1x Car2**	**1x Car3**
$m_{st,}/m_{rot}$ t	62/3,6	60/3,6	84/3,6

Table C.3 — Axle mass distribution

Designation	**2x Trailer Axle 1**	**2x Motor Axle 1**	**2x Trailer Axle 2**	**2x Motor Axle 2**	**6x Trailer Axle3**
Abbreviation	TA1	MA1	TA2	MA2	TA3
$m_{st,ax,}/m_{rot,ax}$ t	15,5/0,6	15,5/1,2	15,0/0,6	15,0/1,2	14,0/0,6

C.1.2 Wheel data

See 5.2.2.3.

Table C.4 — Wheel data

Type of axle	TA1	MA1	TA2	MA2	TA3
D (in mm)	890	890	890	890	890

C.1.3 Train resistance

See 5.2.2.4.

Table C.5 — Train resistance

Designation	RES
A (in N)	1500
B (in N*s/m)	50
C (in N*s²/m²)	3,5

C.1.4 Data for brake equipment types

C.1.4.1 Electro dynamic brake (depending on adhesion)

See 5.3.3.1.

C.1.4.1.1 Parameter of the electro dynamic brake

Table C.6 — Parameter of the electro dynamic brake

Parameter	Designation						
	TA1DB	MA1ED	MA1DB	TA2DB	MA2ED	MA2DB	TA3DB
Quantity		1			1		
$F_{BED,max}$ (in kN)		17			17		
v_j (in km/h)		250			250		
v_2 (in km/h)		118,6			118,6		
v_3 (in km/h)		10			10		
v_4 (in km/h)		5			5		

C.1.4.1.2 Time characteristic of the electro dynamic brake

See 5.3.4.

Table C.7 — Time characteristic of the electro dynamic brake (f(t) %)

t (in s)	Designation						
	TA1DB	MA1ED	MA1DB	TA2DB	MA2ED	MA2DB	TA3DB
0 - 1		0			0		
1 - 2		linear			linear		
≥ 2		100			100		

C.1.4.2 Disc brake (depending on adhesion)

See 5.3.2.3.

C.1.4.2.1 Axle related parameters of the disc brakes

See 5.3.2.3.

Table C.8 — Axle related parameters of the disc brakes

Parameter	Designation						
	TA1DB	MA1ED	MA1DB	TA2DB	MA2ED	MA2DB	TA3DB
A_C (in cm²)	510		510	510		510	510
η_C	1		1	1		1	1
i_C	1		1	1		1	1
$F_{S,C}$ (in kN)	- 1,55		- 1,55	- 1,55		- 1,55	- 1,55
η_{rig}	0,95		0,95	0,95		0,95	0,95
i_{rig}	2,32		2,96	2,32		2,96	2,32
η_{tra}	1		1	1		1	1
i_{tra}	1		1	1		1	1
μ	0,37		0,37	0,37		0,37	0,37
r_s (in mm)	247		247	247		247	247

C.1.4.2.2 Nominal pressure setting of the disc brakes

See 5.3.2.3.

Table C.9 — Nominal pressure setting of the disc brakes, p_C in bar

v (in km/h)	Designation						
	TA1DB	MA1ED	MA1DB	TA2DB	MA2ED	MA2DB	TA3DB
0 - 200	3,15		2,75	3,05		2,65	2,90
200 - 330	2,6		2,1	2,50		2,00	2,35

NOTE The brake force calculation within the integration loop considers the cylinder pressure related to the current calculated train speed. Here the pressure is switched in a step from 2,6 bar to 3,15 bar.

C.1.4.2.3 Time characteristic of the disc brakes

See 5.3.4.

Table C.10 — Time characteristic of the disc brake (f(t) %)

t (in s)	Designation						
	TA1DB	**MA1ED**	**MA1DB**	**TA2DB**	**MA2ED**	**MA2DB**	**TA3DB**
0 - 0,5	0		0	0		0	0
0,5 - 3,5	linear		linear	linear		linear	linear
≥ 3,5	100		100	100		100	100

C.1.5 Characteristics and settings of the brake equipment

C.1.5.1 Brake equipment in use

See 5.4.5.

Table C.11 — Brake equipment in use

	Designation						
	TA1DB	MA1ED	MA1DB	TA2DB	MA2ED	MA2DB	TA3DB
Quantity per axle	3	1	2	3	1	2	3
Brake activated	X	X	-	X	X	-	X

C.1.6 Initial and final speed

See 5.4.2 and 5.10.2.

Table C.12 — Initial and final speed

Initial speed	v_0 (in km/h)	300
Final speed	v_2 (in km/h)	0

C.1.7 Gradient

See 5.4.1.

The gradient *i* is equal to 0.

C.2 Calculation results

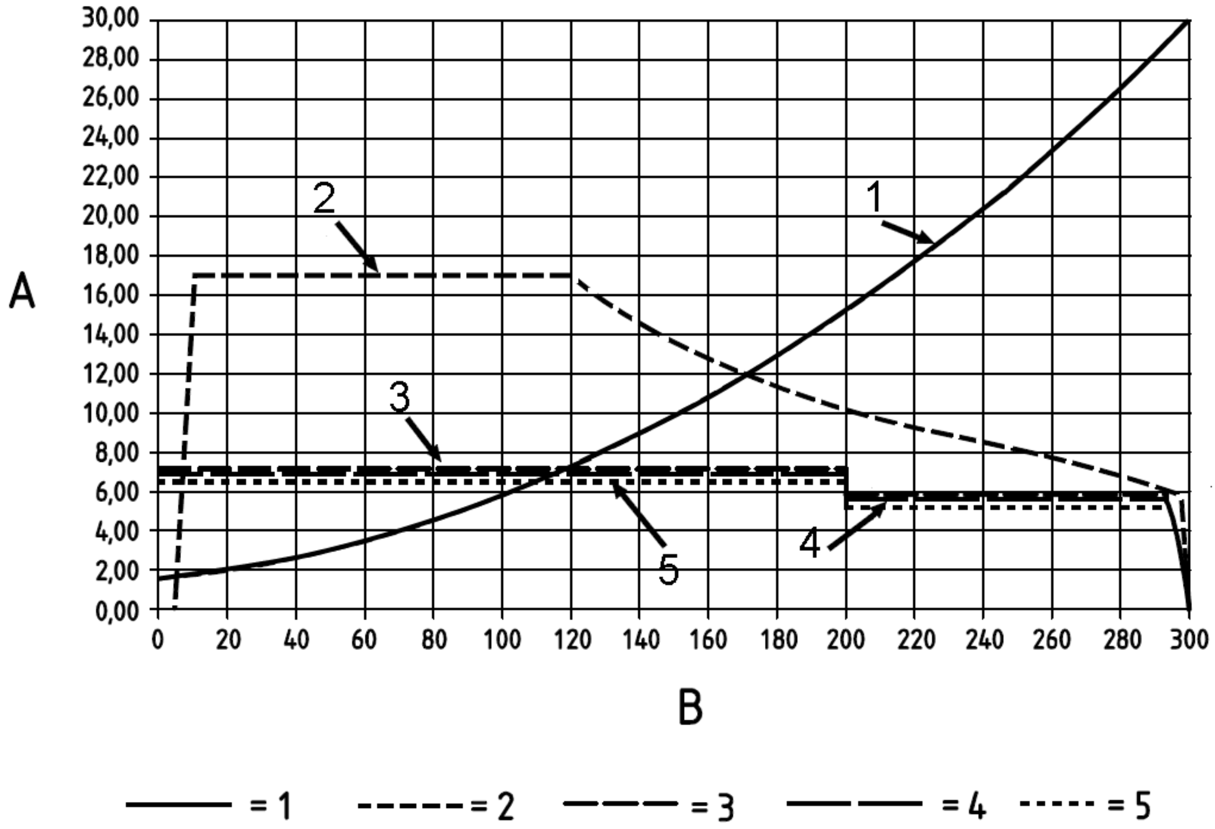
C.2.1 Braking force of single equipments and train resistance

Figure C.1 shows the different braking forces related to the rail (see 5.3.1) of each brake equipment type activated in the calculation and the train resistance versus train speed.

In detail:

a) The braking force $F_{\mathrm{B,i}}$ is shown per single equipment axle related (e.g. TA1 shows the force of one of three disc brakes installed on Axle 1, according to C1.4.2.1).

b) Additional the train resistance F_{Ra} as an external retarding force is plotted (line 1 of Figure C.1) (see C.1.3).



Key

1 Train resistance
2 MA1ED
3 TA1DB
4 TA2DB
5 TA3DB
A Braking force (in kN)
B Speed (in km/h)

Figure C.1 — Braking force of single equipment versus speed and train resistance

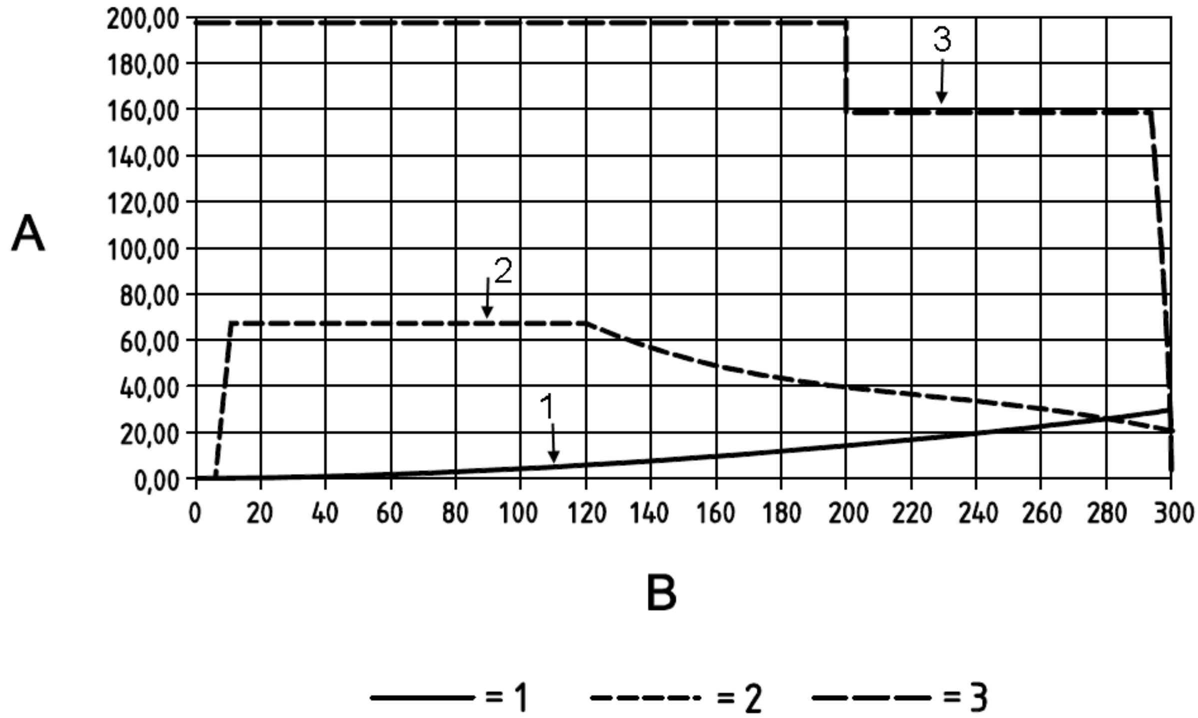
C.2.2 Total braking force per braking equipment type and train resistance

Figure C.2 shows the summation of the braking forces related to specific equipment types and the train resistance versus train speed.

In detail:

a) The braking force $F_{B,i}$ is shown as summation per equipment type (all activated disc brakes $F_{B,C}$ (line 3 of Figure C.2) acc. C.1.4.2; all activated electrodynamic brakes F_{BED} (line 2 of Figure C.2) according to C.1.4.1).

b) Additional the train resistance F_{Ra} as an external retarding force is plotted (line 1 of Figure C.2) (see C.1.3).



Key

1 Train resistance
2 Electrodynamic brake
3 Disc brake
A Braking force (in kN)
B Speed (in km/h)

Figure C.2 — Total braking force versus speed and brake equipment type

C.2.3 Distances

The distance is a direct result of the time integration (see 5.11).

Table C.13 — Distances

Initial speed	v_0 (in km/h)	200	250	300
Distance	s (in m)	1367,3	2 273,4	3 385,1

C.2.4 Stopping time

The stopping time is a direct result of the time integration (see 5.10.2).

Table C.14 — Stopping time

Initial speed	v_0 (in km/h)	200	250	300
Stopping time	t (in s)	47,55	61,66	75,90

C.2.5 Equivalent response time

The equivalent response time is a result of two time integrations according to 5.10.3.

Table C.15 — Equivalent response time

Initial speed	v_0 (in km/h)	200	250	300
Equivalent response time	t_e (in s)	1,79	1,71	1,66

C.2.6 Equivalent deceleration

The equivalent deceleration is a direct result of the time integration (see 5.9.3).

Table C.16 — Equivalent deceleration

Initial speed	v_0 (in km/h)	0 - 170	170 - 230	230 - 300
Equivalent deceleration	a_e (in m/s²)	1,233	1,063	0,972

C.2.7 Decelerations

Figure C.3 shows a conclusion of the deceleration with and without response time versus train speed added by the equivalent deceleration acc. to Directive 96/48/EC and its minimum requirement to it.

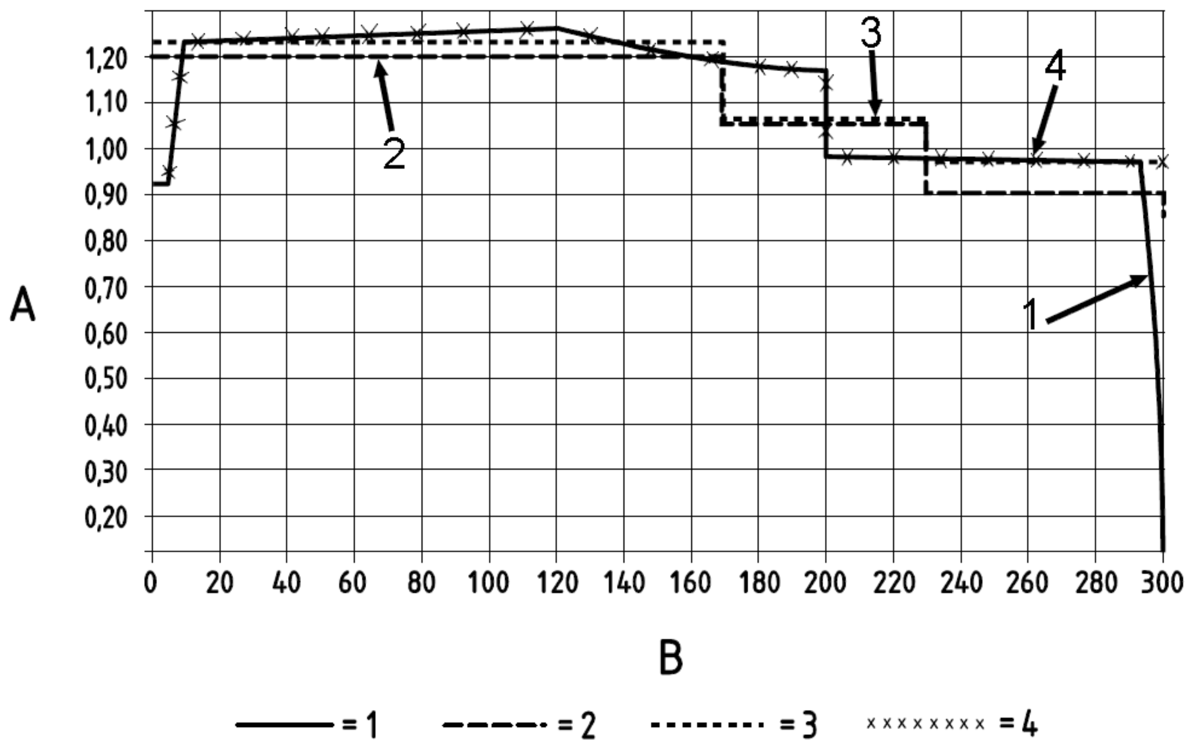
In detail:

a) The train deceleration a_j (line 1 of Figure C.3) is a direct result from the time step integration (see Annex B).

b) The deceleration $a_{f(100\%)}$ (line 4 of Figure C.3) is a direct result from the time step integration without the respect of the response time (see Annex B).

c) The equivalent deceleration a_e (line 3 of Figure C.3) is calculated acc. 5.9.3 and follows the rules in between definite speed ranges defined in Directive 96/48/EC (see also C.2.6).

d) As reference the minimum requirement for the equivalent deceleration according to Directive 96/48/EC $a_{e,TSI;min}$ (line 2 of Figure C.3) is plotted in the figure.



Key

1 Deceleration

2 $a_{\mathbf{TSI,min}}$

3 a_e

4 $a_{j,f(100\%)}$

A Axis for deceleration (in m/s²)

B Axis for speed (in km/h)

Figure C.3 — Deceleration versus speed

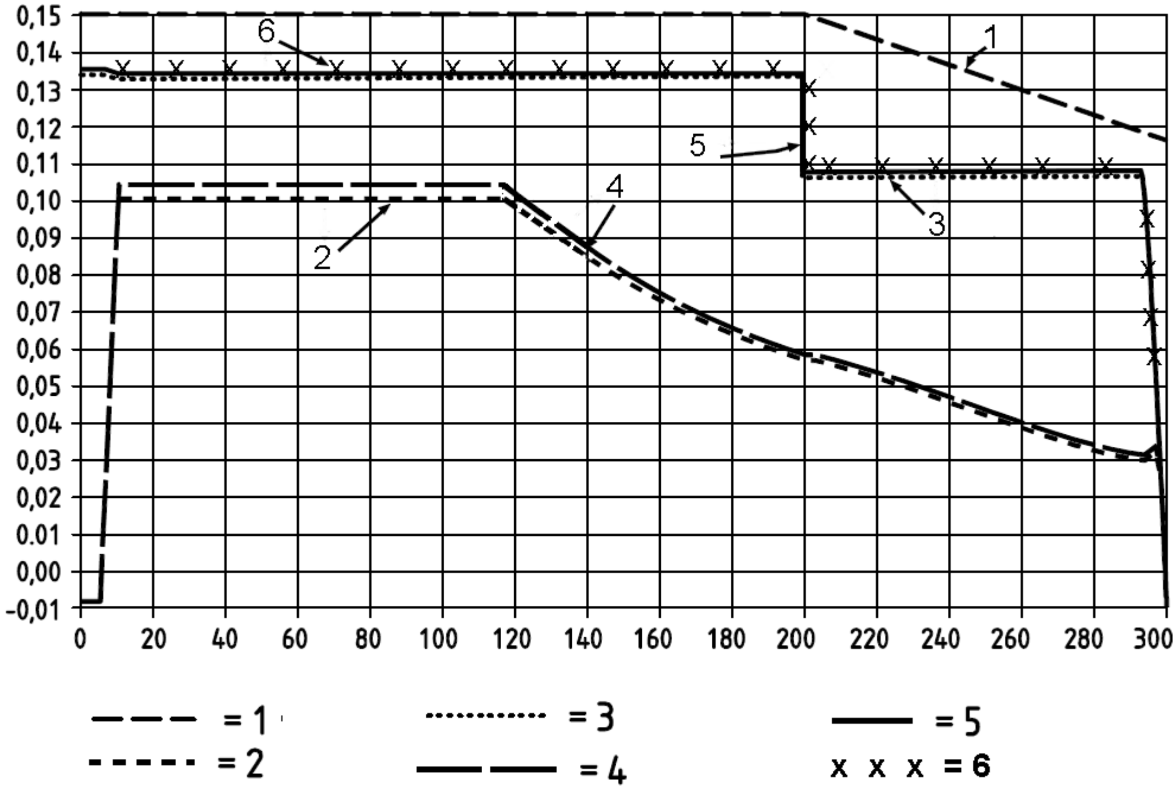
C.2.8 Required adhesion

Figure C.4 shows a conclusion of the required adhesion per axle versus train speed added by the adhesion limit acc. to Directive 96/48/EC and its maximum requirement to it.

In detail:

a) The required adhesion $\tau_{req,ax}$ is shown per axle (TA1, TA2, TA3, MA1, MA2). Here all trailer axles are braked with the disc brakes. The motor axles are only braked by the electrodynamic brakes. The disc brakes of the motor axles are not activated (see 5.12.6).

b) As reference the maximum requirement for the required adhesion acc. Directive 96/48/EC $\tau_{TSI;max}$ (line 1 of Figure C.4) is plotted in the figure.



Key

1 $\tau_{TSI,max}$
2 MA1
3 TA2
4 MA2
5 TA3
6 TA1
A Wheel/rail adhesion
B Speed (in km/h)

Figure C.4 — Wheel/rail adhesion versus speed and axle

Annex D
(informative)

Example of immobilisation calculations

D.1 Input data

The following abbreviations are used in this example:

- TA Trailer Axle
- MA Motor Axle
- ED Electrodynamic Brake
- DB Disc Brake
- RES Train resistance

When the columns are grey in the following tables, it means that they are not concerned for the calculations.

D.1.1 Mass data

See 6.4.

Table D.1 — Train mass distribution

Designation	Train mass distribution
$m_{st,}/m_{rot}$ t	206/10,8

Table D.2 — Car mass distribution

Designation	**1x Car1**	**1x Car2**	**1x Car3**
$m_{st,}/m_{rot}$ t	62/3,6	60/3,6	84/3,6

Table D.3 — Axle mass distribution

Designation	**2x Trailer Axle 1**	**2x Motor Axle 1**	**2x Trailer Axle 2**	**2x Motor Axle 2**	**6x Trailer Axle3**
Abbreviation	TA1	MA1	TA2	MA2	TA3
$m_{st,ax,}/m_{rot,ax}$ t	15,5/0,6	15,5/1,2	15,0/0,6	15,0/1,2	14,0/0,6

D.1.2 Wheel data

See 5.2.2.3.

Table D.4 — Wheel data

Type of axle	TA1	MA1	TA2	MA2	TA3
D (in mm)	890	890	890	890	890

D.1.3 Train resistance

See 6.7.3.

Table D.5 — Train resistance

Designation	**RES**
A (in N)	0

D.1.4 Wind force on the train

See 6.7.2.

Table D.6 — Wind force on the train

Parameter	**Value**
v (in km/h)	100
C (in N/(m/s)²)	3,5
D (-)	1,1

D.1.5 Data for axle related disc brake equipment

See 5.3.2.3.

Table D.7 — Data for axle related disc brake equipment

Parameter	**Designation**						
	TA1DB	MA1ED	**MA1DBP**	TA2DB	MA2ED	**MA2DBP**	**TA3DBP**
Quantity			1			1	1
$n_{b,C}$ -			2			2	2
$F_{n,st}$ kN			29,5			29,5	23,1
η_{tra} -			1			1	1
i_{tra} -			1			1	1
μ_{st} -			0,37			0,37	0,37
r_s mm			247			247	247

D.1.6 Gradient

See 6.7.1.

Table D.8 — Gradient

i (in ‰)"	40
F_g (in kN)	80,74

D.1.7 Available adhesion

The available adhesion need to be compared with the required adhesion to validate the calculation results.

The here available adhesion, given e.g. by a specification, is needed for F_{im} according to 6.6.2.

The available adhesion τ_a is equal to 0,10.

D.1.8 Brake equipment in use

See 6.1.

Table D.9 — Brake equipment in use

	Designation						
	TA1DB	MA1ED	MA1DBP	TA2DB	MA2ED	MA2DBP	TA3DBP
Quantity per axle	-	-	1	-	-	1	1
Brake activated	-	-	X	-	-	X	X

D.2 Calculation results of the immobilisation calculation

D.2.1 Immobilisation force

— Immobilization force per axel, see 6.6.1:

Table D.10 — Immobilisation force

	Designation				
	TA1	MA1DBP	TA2	MA2DBP	TA3DBP
Force per single equipment, $F_{im,\,i}$ kN	0	12,12	0	12,12	9,49
Force per axle, $F_{im,ax}$ kN	0	12,12	0	12,12	9,49

— Total immobilization force of the train, see 6.6.2:

The total immobilization force of the train, F_{im} , is equal to 105,40 kN.

D.2.2 Immobilisation safety factor

See 6.8.1.

The immobilisation safety factor, S_{im} is equal to 1,26.

D.2.3 Required adhesion per axle

The required adhesion (see 6.8.2) need to be compared with the specified available adhesions in D.1.7 to validate the calculation results.

Table D.11 — Required adhesion per axle

Axle	TA1	MA1	TA2	MA2	TA3
$\tau_{req,ax}$ -	0,00	0,06	0,00	0,06	0,06

D.2.4 Maximum achievable gradient

See 6.8.3.

The maximum achievable gradient, i_{max} is equal to 50,8 ‰.

Annex ZA
(informative)

Relationship between this European Standard and the Essential Requirements of EC Directive 2008/27/EC

This European Standard has been prepared under a mandate given to CEN/CENELEC/ETSI by the European Commission and the European Free Trade Association to provide a means of conforming to Essential Requirements of the New Approach Directive 2008/57/EC.

Once this standard is cited in the Official Journal of the European Communities under that Directive and has been implemented as a national standard in at least one Member State, compliance with the clauses of this standard given in table ZA.1 for High speed Rolling Stock, table ZA.2 for Freight wagons and table ZA.3 for Locomotives and Passenger Rolling Stocks, confers, within the limits of the scope of this standard, a presumption of conformity with the corresponding Essential Requirements of that Directive and associated EFTA regulations.

Table ZA.1 – Correspondence between this European Standard, the HS RST TSI dated June 2006 and adopted by EC on 21 February 2008 and Directive 2008/57/EC

Clause/subclauses of this European Standard	Chapter/§of the TSI	Corresponding text, articles/§/annexes of the Directive 2008/57/EC	Comments
The whole standard is applicable	4.2.4.1 Minimum braking performance 4.2.4.2 Brake wheel/rail adhesion demand limits 4.2.4.7 Brake performance on steep gradients	In Annex III, Essential Requirements 1. General requirements 1.1.2 Safety 1.5 Technical compatibility 2 Requirements specific to each Subsystem 2.3 Control and command and signalling 2.3.2§1 Technical compatibility 2.4 Rolling Stock 2.4.1 Safety §3 2.4.2 Reliability and availability 2.4.3 Technical compatibility §3	

Table ZA.2 – Correspondence between this European Standard, the CR TSI Rolling Stock Freight Wagon dated July 2006 and published in the Official Journal on 8 December 2006 and Directive 2008/57/EC

Clause/subclauses of this European Standard	Chapter/§of the TSI	Corresponding text, articles/§/annexes of the Directive 2008/57/EC	Comments
The whole standard is applicable	Chapter 4 Characterisation of the subsystem 4.2. Functional and technical specifications of the subsystem 4.2.4 Braking 4.2.4.1 Braking performance Annex S: Braking, Braking performance	In Annex III, Essential Requirements 1. General requirements 1.1.2 Safety 1.5 Technical compatibility 2 Requirements specific to each Subsystem 2.3 Control and command and signalling 2.3.2§1 Technical compatibility 2.4 Rolling Stock 2.4.1 Safety §3 2.4.2 Reliability and availability 2.4.3 Technical compatibility §3	

Table ZA.3 – Correspondence between this European Standard, the CR TSI Locomotive and Passenger Rolling Stocks (Preliminary draft Rev 1.0 dated 27 August 2008) and Directive 2008/57/EC

Clause/subclauses of this European Standard	Chapter/§of the TSI	Corresponding text, articles/§/annexes of the Directive 2008/57/EC	Comments
The whole standard is applicable	4.2.4 Braking 4.2.4.1 General 4.2.4.5 Braking performance 4.2.4.5.1 General requirements 4.2.4.5.2 Emergency braking	In Annex III, Essential Requirements 1. General requirements 1.1.2 Safety 1.5 Technical compatibility 2 Requirements specific to each Subsystem	Sub clause 4.2.4.5 Braking performance refers to the part 1 of EN 14531 for the performance calculation. Annex d precise that the part 6 should be referred in the TSI. The CR TSI Locomotives and Passenger RST is still a draft subject to

	4.2.4.5.3 Service braking 4.2.4.5.5 Parking brake Annex d Braking performance calculation / Braking performance testing	2.3 Control and command and signalling 2.3.2§1 Technical compatibility 2.4 Rolling Stock 2.4.1 Safety §3 2.4.2 Reliability and availability 2.4.3 Technical compatibility §3	change without notice

WARNING — Other requirements and other EC Directives may be applicable to the product(s) falling within the scope of this standard.

Bibliography

[1] UIC leaflets of the series 540

[2] UIC 540, *Brakes — Air brakes for freight trains and passenger trains*

[3] UIC 541-3, *Brakes — Disc brakes and disc brake pads — General conditions governing bench tests*

[4] UIC 541-4, *Brakes — Brakes with composite brake blocks*

[5] UIC 543, *Brakes — Regulations relative to the equipment of trailing stock*

[6] UIC 544-1, *Brakes — Braking power*

[7] EN 14067-2, *Railway applications - Aerodynamics - Part 2: Aerodynamics on open track*

[8] EN 13452:1-2003, *Railway applications - Braking - Mass transit brake systems - Part 1: Performance requirements*

[9] EN 13452-2:2003, *Railway applications - Braking - Mass transit brake systems - Part 2: Methods of test*

[10] prEN 15734-1, *Railway applications - Braking systems of high speed trains - Part 1: Requirements and definitions*

[11] prEN 15734-2, *Railway applications - Braking systems of high speed trains - Part 2: Test methods*

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