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<u>ISO</u> 20138-2:2019(E) <u>JSO/TC 269/SC 2/WG 1</u>		Deleted: ¶
Railway applications — Calculation of braking performance (stopping, slowing and stationary braking) — Part 2: General algorithms utilizing	, <sup>-</sup>	Formatted: Font: Bold, Font color: Blue
<b>step by step calculation</b> Applications ferroviaires — Calcul des performances de freinage (freinage d'arrêt, de ralentissement et d'immobilisation) — Partie 2: Algorithmes généraux utilisant le calcul pas à pas	· ·	Formatted: Font color: Black

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This document was prepared by Technical Committee ISO/TC 269, Railway applications, Subcommittee

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Foreword

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# Introduction

This document describes methodologies for calculation of braking performance such as stopping distance, deceleration, power and energy for railway rolling stock.

The objective of this document is to enable the railway industry and operators to work with common calculation methods.

The ISO 20138 series consists of two parts (ISO 20138-1 and this document) which complement each other.

This document describes the step by step calculation methods for railway applications applicable to all countries. In addition, the algorithms provide a means of comparing the results of other braking performance calculation methods.

The methodology of step by step calculation is based on numerical time integration.

The step by step calculation method cannot be used for stationary braking. This document considers an example for stationary braking of a multiple unit in accordance with ISO 20138-1.

When calculating stopping and slowing distances using the step by step calculation method, it is intended that both ISO 20138-1 and this document be considered.

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**Deleted: /FDIS** Error! Reference source not found. ISO 20138-2:2019(E) Formatted: Font: (Default) Cambria, 17 pt, Font color: Blue **Railway applications — Calculation of braking performance** (stopping, slowing and stationary braking) — Part 2: General algorithms utilizing step by step calculation Formatted: Font color: Blue 1 Scope This document specifies the methodologies for calculation of braking performance for railway rolling stock. This document describes the general algorithms/formulae using instantaneous value inputs to perform calculations of brake equipment and braking performance, in terms of stopping/slowing distances, braking power and energy for all types of rolling stock, either as vehicles or units, Deleted: , with respect to the braking distance The calculations can be performed at any stage of the assessment process (design, manufacture, testing, Deleted: used verification, investigation, etc.) of railway rolling stock. This document does not set out specific acceptance criteria (pass/fail). This document is not intended to be used as a design guide for the selection of brake systems and does not specify performance requirements. This document does not provide a method to calculate the extension of stopping distances when the level of demanded adhesion exceeds the available adhesion (wheel slide activity). This document contains examples of the calculation of brake forces for different brake equipment types and examples of the calculation of stopping distance for vehicles or units. Deleted: relevant to 2 Normative references The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies. ISO 20138-1:2018, Railway applications — Calculation of braking performance (stopping, slowing and stationary braking) — Part 1: General algorithms utilizing mean value calculation 3 Terms and definitions For the purposes of this document, the terms and definitions given in ISO 20138-1 and the following apply. ISO and IEC maintain terminological databases for use in standardization at the following addresses: ISO Online browsing platform: available at <a href="https://www.iso.org/obp">https://www.iso.org/obp</a> Deleted: https://www.iso.org/ob p IEC Electropedia: available at <a href="http://www.electropedia.org/">http://www.electropedia.org/</a> Deleted: http://www.electropedi a.org/ 3.1 slowing distance S distance run between the initial brake demand and achieving the final speed  $v_{\rm fin}$ 

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Dmin       Wheel diameter min.       m $F_{Bax,st}$ Stationary brake force acting on that wheelset       N $F_{pad,i}$ Force acting on single disc surface ( <i>i</i> is an index used for sorting)       N $F_{r,n}$ Instantaneous retarding force of brake equipment type <i>n</i> N $F_{r,n,j}$ Instantaneous retarding force for brake equipment type <i>n</i> during iteration step <i>j</i> N $F_{r,n,j}$ Instantaneous retarding force for brake equipment type <i>n</i> during iteration step <i>j</i> N $F_{r,n,j}$ Instantaneous retarding force for brake equipment type <i>n</i> during iteration step <i>j</i> N $F_{r,n,j}$ Instantaneous retarding force for brake equipment type <i>n</i> during iteration step <i>j</i> N $F_{r,n,om}$ Nominal retarding force       N $T_{4} = 100 \%$ Index for 100 \% applied braking force without consideration of any time characteristics       — $T_{4}$ Factor (common characteristic) dependent on another variable <i>x</i> — $T_{4}$ Transmission ratio       —	aj	Constant deceleration during iteration step <i>j</i>	m/s <sup>2</sup>	
$T_{F_{Baxst}}$ Stationary brake force acting on that wheelsetN $F_{F_{Baxst}}$ Force acting on single disc surface (i is an index used for sorting)N $F_{r,n}$ Instantaneous retarding force of brake equipment type nN $F_{r,n,j}$ Instantaneous retarding force for brake equipment type n during iteration step jN $F_{r,n,j}$ Instantaneous retarding force for brake equipment type n during iteration step jN $F_{r,nom}$ Nominal retarding forceN $T(t)$ Factor dependent on time $T(t)$ Factor dependent on speed $T(v)$ Factor (common characteristic) dependent on another variable x $T_{ran}$ Transmission ratio	D <sub>max</sub>	Wheel diameter max.	<b>m</b> 7 m	
Fpad.i       Force acting on single disc surface (i is an index used for sorting)       N $F_{r,n}$ Instantaneous retarding force of brake equipment type n       N $F_{r,n,j}$ Instantaneous retarding force for brake equipment type n during iteration step j       N $F_{r,n,j}$ Instantaneous retarding force for brake equipment type n during iteration step j       N $F_{r,n,j}$ Nominal retarding force       N $(t)$ Factor dependent on time $(t)$ Factor dependent on speed $(t)$ Factor dependent on speed $(t)$ Factor (common characteristic) dependent on another variable x $(t_x)$ Factor (common characteristic) dependent on another variable x $(t_x)$ Transmission ratio	D <sub>min</sub>	Wheel diameter min.	m	
Fr.n       Instantaneous retarding force of brake equipment type n       N         Fr.n.d       Instantaneous retarding force for brake equipment type n during iteration step j       N         Fr.n.d       Instantaneous retarding force for brake equipment type n during iteration step j       N         Fr.nom       Nominal retarding force       N         (t)       Factor dependent on time          (t)       Factor dependent on time          (t)       Factor dependent on speed          (t)       Factor dependent on speed          (t)       Factor (common characteristic) dependent on another variable x          (tra       Transmission ratio	F <sub>B,ax,st</sub>	Stationary brake force acting on that wheelset	N	
$F_{r,n,j}$ Instantaneous retarding force for brake equipment type n during iteration step $j_{1}$ N $F_{r,nom}$ Nominal retarding forceN $T(t)$ Factor dependent on time $T(t)$ Factor dependent on time $T(t)$ Factor dependent on speed $T(v)$ Factor dependent on speed $T(x)$ Factor (common characteristic) dependent on another variable x $T_{tra}$ Transmission ratio	F <sub>pad,i</sub>	Force acting on single disc surface ( <i>i</i> is an index used for sorting)	N	
Trad       j       Nominal retarding force       N         Fr.nom       Nominal retarding force       N         It       Factor dependent on time          It       Factor dependent on time          It       Factor dependent on time          It       Factor dependent on speed          It       Factor dependent on speed          It       Factor (common characteristic) dependent on another variable x          It       Transmission ratio	F <sub>r,n</sub>	Instantaneous retarding force of brake equipment type <i>n</i>	Ν	
Fr.nom       Nominal retarding force       N         (t)       Factor dependent on time          (t) = 100 %       Index for 100 % applied braking force without consideration of any time characteristics          (t) = factor dependent on speed           (t) X       Factor (common characteristic) dependent on another variable x          (tra       Transmission ratio	F <sub>r,n,j</sub>	Instantaneous retarding force for brake equipment type <i>n</i> during iteration step	Ν	
(t)       Factor dependent on time       —         (t) = 100 %       Index for 100 % applied braking force without consideration of any time characteristics — — — — — — — — — — — — — — — — — — —	F	Attended a televice at a log/standards/sist/c00df0a0-da2 Nominal retarding force	d-4383-beer N	
Index for 100 % applied braking force without consideration of any time characteristics		20138-2-2019		
Image: Constraint of the sector of the se				
Image: Transmission ratio     Factor (common characteristic) dependent on another variable x	f(t) = 100%			Deleted: )=
Transmission ratio —	<i>f</i> ( <i>v</i> )	Factor dependent on speed	_	
	<i>f</i> ( <i>x</i> )	Factor (common characteristic) dependent on another variable <i>x</i>	—	
	i <sub>tra</sub>	Transmission ratio	—	
Iteration step number —	j	Iteration step number	—	
Pn     Instantaneous braking power of brake equipment type n     W	P <sub>n</sub>	Instantaneous braking power of brake equipment type <i>n</i>	W	
Distance travelled from brake command at time $t_0$ to time $t_j$ m	Sj	Distance travelled from brake command at time $t_0$ to time $t_j$	m	
Distance travelled during iteration step <i>j</i> whilst the brake equipment type <i>n</i> is applied missing the state of the state	S <sub>n,j</sub>		m	
$S_{ref(\Delta t)}$ Stopping/slowing distance, calculated with time step $\Delta t$ m	$S_{ref(\Delta t)}$	Stopping/slowing distance, calculated with time step $\Delta t$	m	
$S_{comp(2 \cdot \Delta t)}$ Stopping/slowing distance, calculated with doubled time step $(2 \cdot \Delta t)$ m	$S_{\text{comp}(2 \cdot \Delta t)}$	Stopping/slowing distance, calculated with doubled time step (2 $\cdot$ $\Delta t$ )	m	
Braking distance without consideration of any time characteristics from initial speed $v_0$ to final speed $v_{fin}$	Sf(4 <u>=100</u> %		<u>m</u>	<b>Deleted:</b> )=
Slowing time/stopping time s	t	Slowing time/stopping time	S	

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Symbol	Definition	Unit
tj	Elapsed time from brake command to <u>iteration</u> step <i>j</i>	S
Δt	Time step	<u>\$</u>
v	Current speed	m/s
Vj	Speed at time <i>t<sub>j</sub></i>	m/s
V <sub>1,ECB</sub>	Deactivating speed of eddy current brake	m/s
8	Speed deviation from $v_{\rm fin}$	m/s
μ	Coefficient of friction (brake pad or block)	_
ξ	Relative distance deviation	%
$ au_{\mathrm{ax}}$	Value of the instantaneous adhesion required between wheel and rail for the braked wheelset	_
$ au_{ m req}$	Required wheel/rail adhesion	_

## 5 General explanation of step-by-step calculation

#### 5.1 Method

The step-by-step method is used when it is not appropriate or desirable to represent the non-constant retarding and braking forces by mean values. Further details of when the use of mean value calculations is appropriate are given in ISO 20138-1.

Time steps are defined in such a way that the braking forces can be considered as constant throughout each step's duration. The duration of each step can depend on changes in the braking force and is not necessarily fixed (i.e. algorithms can be based either on constant or adaptive time step integration schemes). Each time step is characterised by an initial state and a final state, e.g. an initial and a final speed.

For each time step, the distance travelled during that time step as well as the final speed are calculated and the deceleration at the end of that time step is calculated according to Newton's laws. The outputs of the calculations for each time step are used as inputs to the calculations for each subsequent time step.

The calculation shall be done in accordance with the workflow as shown in Annex A.

### 5.2 Retarding force models

Mathematical models for common brake systems (e.g. magnetic track brakes, electrodynamic brakes, etc.) are described in Annex B. The mathematical models for disc brakes, tread brakes and external deceleration forces (e.g. wind forces, running resistance) are described in ISO 20138-1.

The impact of time, speed, load, temperature, etc. on the nominal retarding force can also be expressed in terms of dimensionless factors (functions), e.g. time dependency f(t), speed dependency f(v), etc. Thus, any deceleration force characteristics due to brake system applications or acting external forces (e.g. wind forces) can be modelled.

These dimensionless factors can take effect at the same time and are thus superposed by multiplication as set out in Formula (1).

$$F_{\rm r} = F_{\rm r,nom} \cdot f(t) \cdot f(v) \cdot \dots \cdot f(x) \tag{1}$$

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#### where

$F_{ m r}$	is the instantaneous retarding force acting at the rail generated by the brake equipment, expressed in N;
F <sub>r,nom</sub>	is the nominal retarding force, expressed in N;
f(t)	is the factor dependent on time;
f(v)	is the factor dependent on speed;
f(x)	is the factor (common characteristic) dependent on another variable <i>x</i> .
NOTE For	nominal retarding forces $F_{r,nom}$ , the factors $f(t)$ , $f(v)$ and $f(x)$ are equal to 1.

## 5.3 Algorithm

### 5.3.1 General description

Instantaneous values are the input data for step-by-step (iterative) calculation. The workflow of Figure A.1 shall be used for performing stopping and slowing calculations.

The numerical integration is time-based.

Every calculation begins with the initial brake demand and the initial vehicle/unit speed.

The initial time step begins at time  $t_0 = 0$  s simultaneously with the start of the braking demand. The braking forces which are acting in the initial time step are calculated.

The result of the first iteration step refers to j = 1, i.e.  $v_1 = v_0 - a_0 \Delta t$ , whereas initial values (e.g. initial speed) refer to index j = 0.

The vehicle/unit speed at the end of the time step and the distance travelled during this time step are calculated.

The value of the selected parameter (e.g. speed, distance) at the end of the time step is compared with its target value. <u>https://standards.iteh.arcatalog/standards.ist/c99df9a0-da3d-4383-beed-2526f877efb4/iso</u>

If the target value has not been reached, the calculations are repeated for the next time step.

The time step calculation continues until the target value is reached.

## 5.3.2 Time integration

The time integration should continue until the calculated value of the selected parameter (e.g. speed) is considered equal to the target value of that parameter, i.e. when the condition given in Formula (2) is achieved (where speed is used as an example selected parameter):

 $|v_j - v_{\text{fin}}| < \varepsilon$ 

where

 $v_j$  is the speed at time  $t_j$ , expressed in m/s;

 $v_{\rm fin}$  is the final speed, expressed in m/s;

 $\varepsilon$  is the speed deviation from  $v_{\text{fin}}$ , expressed in m/s.

A speed deviation not greater than 10<sup>-3</sup> m/s is considered as suitable for high speed train calculations. For lower speeds or slowing calculations, other values may be used.

Based on the calculation of retarding forces and external forces, the constant deceleration  $a_j$  during iteration step *j* can be calculated as set out in Formula (3):

(2)

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(3)

$$a_{j} = \frac{\left(\sum F_{\mathrm{r},n} + \sum F_{\mathrm{ext}}\right)_{j}}{m_{\mathrm{dyn}}}$$

where

- j is the iteration step number;
- is the constant deceleration during iteration step *j*, expressed in m/s<sup>2</sup>;  $a_j$
- is the instantaneous retarding force of brake equipment type *n*, expressed in N;  $F_{r,n}$
- is the external force, expressed in N;  $F_{\text{ext}}$
- $m_{
  m dyn}$ is the dynamic mass, expressed in kg.

## If the target value of the selected parameter has not been achieved, the next time step integration is conducted, utilising the outputs of the preceding step, as shown in Formulae (4) to (8):

Speed	l at start of step $t_{j+1}$	$v_{j+1} = v_j - a_j \cdot \Delta t$	(4)	[	<b>Deleted:</b> $v_{j+1} = v_j - a_j \cdot \Delta t$
Dista	nce at start of step $t_{j+1}$	$s_{j+1} = s_j + v_j \cdot \Delta t - \frac{1}{2} \cdot a_j \cdot \Delta t^2$	(5)		<b>Deleted:</b> $s_{j+1} = s_j + v_j \cdot \Delta t - \frac{1}{2} \cdot v_j$
Decel	eration during step $t_{j+1}$	$a_{j+1} = \frac{\left(\sum F_{r,n} + \sum F_{ext}\right)_{j+1}}{m_{dyn}}$	(6)		Field Code Changed Deleted: $a_{j+1} = \frac{\left(\sum F_{r,n} + \sum F_{ext}\right)}{m_{dyn}}$
Next	time step	$t_{j+1} = t_j + \Delta t$	(7)	(	Field Code Changed
Next	time increment	$\frac{ \text{ISO 20138-2:2019}}{j \rightarrow j+1}$	(8)		<b>Deleted:</b> $t_{j+1} = t_j + \Delta t$
h	ttps://standards.iteh.a	i <mark></mark> /standards/sist/c99df9a0-da3d-4383-beed-	2526	871	Field Code Changed
where					<b>Deleted:</b> $j \rightarrow j+1$
aj	is the constant decelera	tion during iteration step <i>j</i> , expressed in m/s <sup>2</sup> ;		1	Field Code Changed
$F_{\mathrm{r},n}$	is the instantaneous ref	arding force of brake equipment type <i>n</i> , expressed in N;			
$F_{\rm ext}$	is the external force, ex for accelerating force <b>n</b>	pressed in N (for decelerating force <b>positive</b> value, <b>egative</b> value);			
j	is the iteration step nur	nber;			
$m_{ m dyn}$	is the dynamic mass, ex	pressed in kg;			
$S_j$	is the distance travelled	l from brake command at time $t_0$ to time $t_{j_i}$ expressed in m;			
$t_j$	is the elapsed time from	n brake command to <u>iteration</u> step <i>j</i> , expressed in s;		(	Deleted: integration
$\Delta t$	is the time step, expres	sed in s	4	[	Formatted: Font: (Default)
	time step sometimes need r (see 5.3.1).	s to be adjusted, if necessary, to meet the target value of the sele	ected		Cambria, 11 pt, Not Bold, Not Italic, Font color: Auto
Other mor	re detailed algorithms ma	y be used if considered necessary.		(	Deleted: ,

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### 5.3.3 Determination of time step/relative distance deviation $\xi$

The relative distance deviation  $\xi$  has to be calculated if the applied integration procedure imposes constant time steps. If an adaptive time integration is used, the requirements in this clause are not applicable.

The time step  $\Delta t$  shall be chosen in such a way that the relative distance deviation is not greater than the minimum precision required. The relative distance deviation  $\xi$  is obtained by two separate integrations. The original calculation with time step  $\Delta t$  determines the reference stopping/slowing distance  $s_{\text{ref}(\Delta t)}$  and the second integration with doubled time step  $2 \cdot \Delta t$  determines a new stopping/slowing distance  $s_{\text{comp}(2 \cdot \Delta t)}$  for comparison. The relative distance deviation  $\xi$  is calculated in accordance with Formula (9) and shall not be greater than the minimum precision required.

The value of the relative distance deviation  $\xi$  shall not exceed a predefined limit value and can be calculated as set out in Formula (9):

$\xi = \frac{\left \frac{S_{\text{comp}}(2\Delta t) - S_{\text{ref}}(\Delta t)}{S_{\text{ref}}(\Delta t)}\right  \cdot 100 \tag{9}$	$\xi = \left  \frac{s_{\text{comp}(2:\Delta t)} - s_{\text{ref}(\Delta t)}}{s_{\text{ref}(\Delta t)}} \right  \cdot 10$ Deleted:
where	Field Code Changed
$\xi$ is the relative distance deviation, expressed in %;	
$s_{\text{ref}(\Delta t)}$ is the stopping/slowing distance, calculated with time step $\Delta t$ , expressed in m;	<b>Formatted:</b> Font: (Default) Cambria, 11 pt, Not Bold, Not Italic, Font color: Auto
$s_{\text{comp}(2,\Delta t)}$ is the stopping/slowing distance, calculated with doubled time step $(2 \cdot \Delta t)$ , expressed in m.	Formatted: Font: (Default) Cambria, 11 pt, Not Bold, Not Italic, Font color: Auto
Usually, a relative distance deviation of $\xi \le 0,1\%$ is considered as acceptable. For low speeds and slowing calculations, greater values of deviation ratio may be used.	
NOTE The definition of validation requirements of any numerical integration procedure is outside the scope of	
this document. https://standards.iteh.ai/catalog/standards/sist/c99df9a0-da3d-4383-beed-25	
5.3.4 Equivalent system response time <u>te</u> 20138-2-2019	<b>Formatted:</b> Font: (Default) Cambria, 11 pt, Not Bold, Font color: Auto
The calculation of equivalent system response time allows the assumption that braking consists first of a "free running time" with braking force equal to zero, followed by a braking time with fully applied braking force. ISO 20138-1 describes the equivalent response time when considering the free running time.	
The equivalent system response time $t_e$ based on stopping and braking distance shall be calculated with two separate time integrations:	
a) the stopping/slowing distance calculated taking into account the time characteristics of each acting brake equipment type starting at time $t_0 = 0$ s simultaneously with the start of the braking demand until achieving the <u>final</u> speed $v_{fin}$ ;	Deleted: target
b) the stopping/slowing distance calculated assuming each acting brake equipment type fully applies (100 %) at time $t_0 = 0$ s simultaneously with the start of the braking demand until achieving the final speed $y_{\text{fin}}$ .	Deleted: target
The equivalent system response time can be calculated as set out in Formula (10).	
$t_{\rm e} = \frac{\frac{S - S_f(t) = 100\%}{v_0}}{(10)}$	$t_{e} = \frac{s - s_{f(t)} = 100\%}{v_{0}}$ Deleted:
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where		l	
$v_0$	is initial speed, in m/s;		
S	is the stopping/slowing distance with all time characteristics taken into account, expressed in m;		Deleted: -
Sf(t) = 10		5	Deleted: )=
	<u>speed v<sub>0</sub> to final speed v<sub>fin</sub>.</u>		Deleted: stopping/slowing
5.4 Suppl	ementary dynamic calculations	Ň	<b>Deleted:</b> assuming all brake equipment fully applies at braking
5.4.1 Ener	gy dissipated by each brake equipment type		demand, expressed in m
ISO 20138 forces.	1 describes the calculation of energy dissipated during braking based on mean retarding		
	energy dissipated by each brake equipment type during iteration steps $j = 0$ to $j = J$ can be based on instantaneous values as set out in Formula (11).		
<i>W</i> <sub>B,<i>n</i></sub> =	$\sum_{j=0}^{J} \left( F_{\mathbf{r},n,j} \cdot s_{n,j} \right) $ (11)		
where			
$W_{\mathrm{B},n}$	is the energy dissipated by brake equipment type <i>n</i> , expressed in J;		
$F_{\mathrm{r},n,j}$	is the instantaneous retarding force for brake equipment type <i>n</i> during iteration step <i>j</i> , expressed in N;		
S <sub>n,j</sub>	is the distance travelled during iteration step $j$ whilst the brake equipment type $n$ is applied, expressed in m.		
5.4.2 Valu wheelset	e of the instantaneous adhesion required between wheel and rail for the braked $-2526$ $\tau_{ax}$ ) 20138-2-2019		
	of the instantaneous adhesion required between wheel and rail for the braked wheelset can ed as set out in Formula (12).		
$\tau_{ax} = -$	$\sum_{n=1}^{N} F_{\mathrm{r},n} - m_{\mathrm{rot},\mathrm{ax}} \cdot a \over m \cdot a} \cdot \sqrt{i^2 + 1} $ (12)		Deleted: $\tau_{ax} = \frac{\sum_{n=1}^{N} F_{r,n} - m_{rot}}{m_{rot}}$

where

- is the value of the instantaneous adhesion required between wheel and rail  $au_{\mathrm{ax}}$ for the braked wheelset;
- Ν is the number of brake equipment types;

 $m_{\mathrm{st,ax}} \cdot g$ 

- $\sum_{n=1}^{N} F_{\mathbf{r},n}$ is the sum of all adhesion dependent retarding forces from all brake equipment types per wheelset, expressed in N;
- $F_{\mathrm{r},n}$ is the instantaneous retarding force of brake equipment type *n*, expressed in N;
- is the instantaneous deceleration of the vehicle/unit, expressed in  $m/s^2$ ; а
- is the standard acceleration due to gravity, expressed in m/s<sup>2</sup>; g

 $m_{\mathrm{st,ax}} \cdot g$ 

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