Proposed New Formulae for Brake Testing and In-service Performance

1.0 Summary

For practical application the following equations should be used.

Equations '*A1*', '*B1*' & '*C1*' should be used for design or '*type*' testing to ISO 3450:1996 or AS 2958.1:1995. They allow adjustment for brake pressure variations for secondary brake performance testing.

Equations '*A2*', '*B2*' & '*C2*' should be used for '*in service*' site dynamic testing, of a particular machine. It allows adjustments where dynamic testing is not carried out at the machine gross vehicle mass (GVM).

Equation A1
$$a_{brake-test} = \left(a_{safe-nett} + g(D-T)\right)\left(\frac{100}{100-P}\right)$$

Equation A2
$$a_{brake-test} = \left(a_{safe-nett} + g(D-T)\right)\left(\frac{m_{GVM}}{m_{actual}}\right)$$

Equation B1
$$s = \left(\frac{V^2}{25.92\left[a_{safe-nett} + g(D-T)\right]}\right)\left(\frac{100-P}{100}\right)$$

Equation B2
$$s = \left(\frac{V^2}{25.92\left[a_{safe-nett} + g(D-T)\right]}\right)\left(\frac{m_{actual}}{m_{GVM}}\right)$$

Equation C1
$$\beta = 100\tan\sin^{-1}\left[\frac{\left(\left(\frac{100-P}{100}\right)(a_{brake-test}) - a_{safe-nett}\right)}{g} + T\right]$$

Equation C2
$$\beta = 100\tan\sin^{-1}\left[\frac{\left(\left(\frac{m_{actual}}{m_{GVM}}\right)(a_{brake-test}) - a_{safe-nett}\right)}{g} + T\right]$$

Where

D	=	design grade function = $\dfrac{\beta}{\sqrt{100^2 + \beta^2}}$
T	=	test grade function = $\dfrac{\alpha}{\sqrt{100^2 + \alpha^2}}$
V	=	the test velocity of the machine immediately prior to the brake control being activated (km/h)
s	=	the minimum acceptable stopping distance along the test grade (m)
P	=	percentage reduction in braking force, such as change in brake application pressure
m_{actual}	=	actual mass of the machine being tested (kg)
m_{GVM}	=	rated gross vehicle mass (GVM) of the machine (kg)
g	=	acceleration due to gravity = 9.81 (m/s^2)
α	=	test grade as a percentage, e.g. if α = 9, the test grade is 9% or $\dfrac{9}{100}$
β	=	maximum design grade as a percentage, e.g. β = 9 for a 9% grade Note: β must not be less than 10
$a_{brake-test}$	=	the mean minimum acceptable deceleration for the vehicle when measured along the test grade (m/s^2)
$a_{safe-nett}$	=	the mean minimum safe nett deceleration to pull up the machine in the safest and shortest practicable time. (m/s^2).

Use of Equation 'A' ($a_{safe-nett}$)

Our recommended minimum values for $a_{safe-nett}$ when the machine is being operated in service are:

Service brake application	$a_{safe-nett}$ = 0.60 m/s^2
Secondary brake application	$a_{safe-nett}$ = 0.30 m/s^2

For type testing of a new machine, there needs to be a tolerance above these figures to allow for wear and variations between machines from manufacturing.

This tolerance should be 125% of the minimum acceptable.

Our recommended minimum values for $a_{safe-nett}$ when a new machine is type tested are:

Service brake application	$a_{safe-nett}$ = 0.75 m/s^2
Secondary brake application	$a_{safe-nett}$ = 0.40 m/s^2

Note:

1. The value calculated by $a_{safe-nett}$ is the mean minimum safe nett deceleration (or stopping distance) to pull up the machine in the safest and shortest practicable time. The value calculated by equation 'A' above should be compared against the actual mean decelerations measured during the brake performance tests.
2. If the actual mean deceleration is less than the calculated $a_{safe-nett}$, then the result is a failure.
3. This minimal acceptable deceleration could be varied for regional requirement, for different types of machines for different machine speeds and/or for different system response times.
4. However, there appears to be no justification from a safety perspective to vary these figures.

Use of Equation 'B' (s)

Equation 'B' provided the minimum acceptable stopping distance along the test grade. This is analogous to the existing equations in ISO 3450 and AS 2958.1.

The main difference is it calculates the safe minimum acceptable stopping distance for designed maximum operating grade rather than the test grade as per the existing formula.

Use of Equation 'C' (β)

Equation 'C' provides the maximum design grade that the truck is able to be operated on, based on the minimum acceptable $a_{safe-nett}$.

For type (design) testing, this formula (C1) can be used as a design verification tool to calculate the maximum grade based on actual brake testing results.

For in service applications, this formula (C2) can be used to verify the actual brakes on a particular machine are able to stop the machine on a specified grade on site.

NOTE:

All of the above equations assume that:

1. There is traction between the wheels and the test surface, and
2. There is no skidding between the wheels and the test surface

2.0 Examples

2.1 Example 1 – Design Testing Service Brake

Design (type) testing of a rigid Dump Truck with a rated gross vehicle mass of 100,000 kg, including payload.

- The maximum speed of the truck 40 km/h
- The maximum design grade of the truck is 20%
- $a_{safe-nett}$ = 0.75 (m/s^2) – service brakes

ISO 3450 and AS 2958.1 require this truck to be tested on a 9% grade. Therefore:

Testing on a 9% grade test course

a) If the required deceleration on the test course is to be checked against a brake meter reading, use *Equation A1*

Equation A1 $$a_{brake-test} = \left(a_{safe-nett} + g\left(D-T\right)\right)\left(\frac{100}{100-0}\right)$$

$$= \left(0.75 + g\left(D-T\right)\right)\left(\frac{100}{100-0}\right)$$

$$= 1.79(m/s^2)$$

where $D = \frac{20}{\sqrt{100^2+20^2}} = 0.196116$

$T = \frac{9}{\sqrt{100^2+9^2}} = 0.0896377$

Therefore,

- If the actual mean measured deceleration < 1.79 m/s^2, the result is a failure. The design grade is too high.
- If the actual mean measured deceleration > 1.79 m/s^2, the result is a pass.

b) If a brake meter is not used, but the speed and stopping distance are measured, then the maximum stopping distance on a 9% grade test course is calculated using *Equation B1*

Equation B1 $$s = \left(\frac{V^2}{25.92\left[a_{safe-nett} + g\left(D-T\right)\right]}\right)\left(\frac{100-0}{100}\right)$$

$$= \left(\frac{40^2}{25.92\left[0.75 + 9.81\left(0.196116 - 0.0896377\right)\right]}\right)\left(\frac{100-0}{100}\right)$$

$$= 34.4(m)$$

As above, this is the minimum stopping distance for a design grade of 20%.

where $D = \frac{20}{\sqrt{100^2 + 20^2}} = 0.196116$

$$T = \frac{9}{\sqrt{100^2 + 9^2}} = 0.0896377$$

2.2 *Example 2 – Design Testing Service Brake*

Design (type) testing of am articulate rear Dump Truck with a rated gross vehicle mass of 25,000 kg, including payload.

- The maximum speed of the truck 50 km/h
- The maximum design grade of the truck is 25%
- $a_{safe-nett}$ = 0.75 (m/s^2) – service brakes

ISO 3450 and AS 2958.1 require this truck to be tested on a the level. Therefore:

<u>Testing on a level test course</u>

a) If the required deceleration on the test course is to be checked against a brake meter reading, use *Equation A*

Equation A1 $a_{brake-test} = \left(a_{safe-nett} + g(D - T)\right)\left(\frac{100}{100 - P}\right)$

$$= \left(0.75 + 9.81(0.24254 - 0)\right)\left(\frac{100 - 0}{100}\right)$$

$$= 3.13(m/s^2)$$

Therefore,

- If the actual mean measured deceleration < 3.13 m/s^2, the result is a failure. The design grade is too high.
- If the actual mean measured deceleration > 3.13 m/s^2, the result is a pass.

where $D = \frac{25}{\sqrt{100^2 + 25^2}} = 0.24254$

$$T = \frac{0}{\sqrt{100^2 + 0^2}} = 0$$

b) If a brake meter is not used, but the speed and stopping distance are measured, then the maximum stopping distance on a level test course is calculated using *Equation B*

Equation B1 $s = \left(\frac{V^2}{25.92\left[a_{safe-nett} + g(D-T)\right]} \right)\left(\frac{100-P}{100} \right)$

$$= \left(\frac{50^2}{25.92\left[0.75 + 9.81(0.24254 - 0)\right]} \right)\left(\frac{100-0}{100} \right)$$

$$= 30.82(m)$$

As above, this is the minimum stopping distance for a design grade of 25%.

where $D = \frac{25}{\sqrt{100^2 + 25^2}} = 0.24254$

$$T = \frac{0}{\sqrt{100^2 + 0^2}} = 0$$

2.3 Example 3 – In Service Testing

An old machine is supplied to a site and testing is to be done to see if it can be used. It is an articulated Dump Truck with a rated gross vehicle mass (GVM) of 60,000 kg,

- The test speed of the truck is recorded at 32 km/h.
- The maximum grade on the site is 13%
- The manufacturer says the truck is designed for 15% grade.
- $a_{safe-nett}$ = 0.6 (m/s^2) – service brakes in service criteria
- The machine can only be loaded to an actual mass of 50,000 kg.

Can this particular machine be safely used on the site?

This test is done on site on a level test course

a) If a brake meter is used for the test, use *Equation A.*

Equation A2 $a_{brake-test} = \left(a_{safe-nett} + g(D-T)\right)\left(\frac{m_{GVM}}{m_{actual}} \right)$

$$= \left(0.60 + 9.81(0.128915 - 0)\right)\left(\frac{60000}{50000} \right)$$

$$= 2.24(m/s^2)$$

Therefore

- If the actual mean measured deceleration < 2.24 m/s^2, the result is a failure. The truck cannot be used on a 13% grade at gross vehicle mass.

- If the actual mean measured deceleration > 2.24 m/s^2, the result is a pass.

where $D = \frac{13}{\sqrt{100^2 + 13^2}} = 0.128915$

$$T = \frac{0}{\sqrt{100^2 + 0^2}} = 0$$

This test was done at full brake pressure of 100 psi

b) If a brake meter is not used, but the speed and stopping distance are measured, then the maximum stopping distance on a level test course is calculated using *Equation B2*

Equation B2 $s = \left(\frac{V^2}{25.92\left[a_{safe-nett} + g\left(D - T\right)\right]} \right) \left(\frac{m_{actual}}{m_{GVM}} \right)$

$$= \left(\frac{32^2}{25.92\left[0.60 + 9.81\left(0.128915 - 0\right)\right]} \right) \left(\frac{60000}{50000} \right)$$

$$= 25.42(m)$$

where $D = \frac{13}{\sqrt{100^2 + 13^2}} = 0.128915$

$$T = \frac{0}{\sqrt{100^2 + 0^2}} = 0$$

As above, this is the minimum stopping distance for on the level for the machine to be safe to operate on the 13% grade.

2.4 Example 4 - Comparison to ISO 3450 & AS 2958.1

SERVICE BRAKES OF MACHINES TESTED ON THE LEVEL

Machines tested with payload except rigid frame or articulated dumpers with a machine mass over 32 000 kg

That is, the example machines are < 32 000 kg

The tests are carried out on a level test course. That is $\alpha = 0\%$

NOTE: all stopping distances in this table are those measured along the level test course in order to stop on the design grade at the shown deceleration rates of: $a_{safe-nett}$ *(m/s²)*

Test Speed (V)	**STOPPING DISTANCE (m)**						
	Design grade ISO 3450:1996	**Design Criteria $a_{safe-nett} = 0.75$ (m/s)**			**In Service Criteria $a_{safe-nett} = 0.60$ (m/s)**		
(km/hr)	**β = Not stated**	**β = 10%**	**β = 15%**	**β = 20%**	**β = 10%**	**β = 15%**	**β = 20%**
5	3.2	0.6	0.4	04	0.6	0.5	0.4
10	4.4	2.2	1.8	1.4	2.5	1.9	1.5
15	6.8	5.0	3.9	3.3	5.5	4.2	3.4
20	10.3	8.9	7.0	5.8	9.8	7.5	6.1
25	14.9	14.0	10.9	9.0	15.3	11.7	9.6
30	20.7	20.1	15.8	13.0	22.0	16.9	13.8
35	23.3	27.4	21.4	17.7	30.0	23.0	18.7
40	36.4	35.8	28.0	23.1	39.2	30.0	24.5
45	46.0	45.3	35.4	29.2	49.6	38.0	31.0
50	56.8	55.9	43.7	36.1	61.2	46.9	38.2

2.5 *Example 5 - Comparison to ISO 3450 & AS 2958.1*

SERVICE BRAKES OF MACHINES TESTED ON 9% GRADE

Rigid frame and articulated steer dumpers with a machine mass over 32 000 kg

The example machines are > 32 000 kg

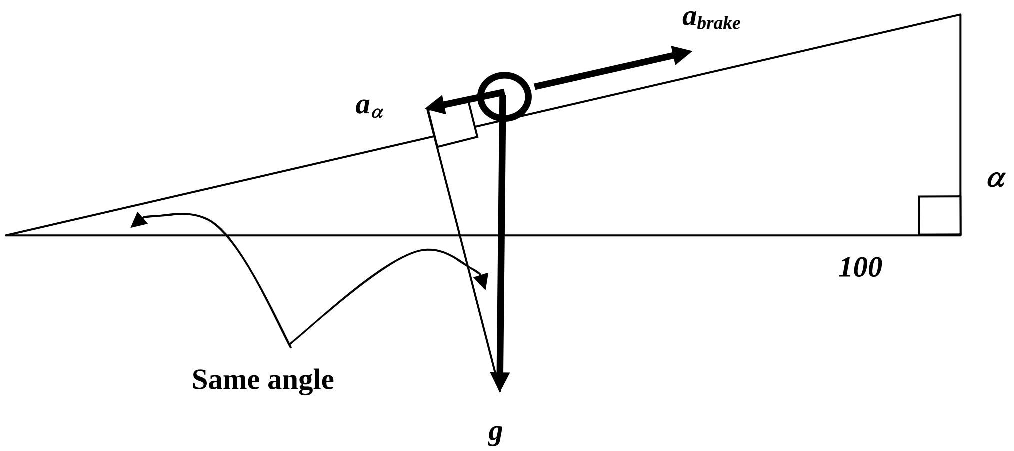
The tests are carried out on a test course with a 9% grade. That is $\alpha = 9\%$

NOTE: all stopping distances in this table are those measured along the 9% grade test course in order to stop on the design grade at the shown deceleration rates of: $a_{safe-nett}$ *(m/s²)*

Test Speed (V)	**STOPPING DISTANCE (m)**						
	Design grade ISO 3450:1996	**Design Criteria** $a_{safe-nett} = \mathbf{0.75\ (m/s)}$			**In Service Criteria** $a_{safe-nett} = \mathbf{0.60\ (m/s)}$		
(km/hr)	β **= Not stated**	β **= 10%**	β **= 15%**	β **= 20%**	β **= 10%**	β **= 15%**	β **= 20%**
5	1.0	1.1	0.7	0.5	1.4	0.8	0.6
10	4.1	4.6	2.9	2.2	5.5	3.3	2.4
15	9.2	10.3	6.6	4.8	12.5	7.4	5.3
20	16.3	18.2	11.6	8.6	22.2	13.1	9.4
25	25.4	28.5	18.2	13.4	34.6	20.5	14.7
30	36.6	41.0	26.2	19.4	19.8	29.5	21.1
35	49.8	55.8	35.7	26.3	67.8	40.2	28.7
40	65.0	72.9	46.6	34.4	88.6	52.5	37.5
45	82.3	92.3	58.9	43.5	112.1	66.4	47.5
50	101.6	113.9	72.7	53.8	138.4	82.0	58.7

3.0 Derivation of Formulae

3.1 Service And Secondary Brake Testing On A Test Grade



Braking accelerations during brake testing on a test grade of α %

The deceleration on the test grade is

Equation 1 $a_{brake-test} = a_{brake} - a_{\alpha}$

Where $a_{brake-test}$ = acceleration measured along the test grade (m/s^2)

a_{brake} = maximum braking deceleration on level ground (m/s^2)

a_{α} = acceleration along the test grade due to gravity (m/s^2)

And a_{α} can be calculated from

Equation 2a $a_{\alpha} = g \sin \tan^{-1}\left(\frac{\alpha}{100}\right)$

Where g = acceleration due to gravity = 9.81 (m/s^2)

α = test grade as a % for example, if α = 9, the test grade is 9% or $\frac{9}{100}$

This equation can be rewritten as:

Equation 2b $a_{\alpha} = g\left(\frac{\alpha}{\sqrt{100^2 + \alpha^2}}\right)$

Now if $T = \dfrac{\alpha}{\sqrt{100^2 + \alpha^2}}$ = test grade function (T), then *Equation 2b* can be rewritten as

Equation 2c $a_\alpha = g(T)$

Clearly when the test grade is level, $\alpha = 0$ and $a_\alpha = 0$. *Equation 1* then yields $a_{brake-test} = a_{brake}$

When a brake meter is not used to measure $a_{brake-test}$ directly, it can be calculated from

Equation 3a $a_{brake-test} = \dfrac{v^2}{2s}$

Substituting "V" (km/h) for "v" (m/s) in this equation gives

Equation 3b $a_{brake-test} = \dfrac{V^2}{25.92s}$

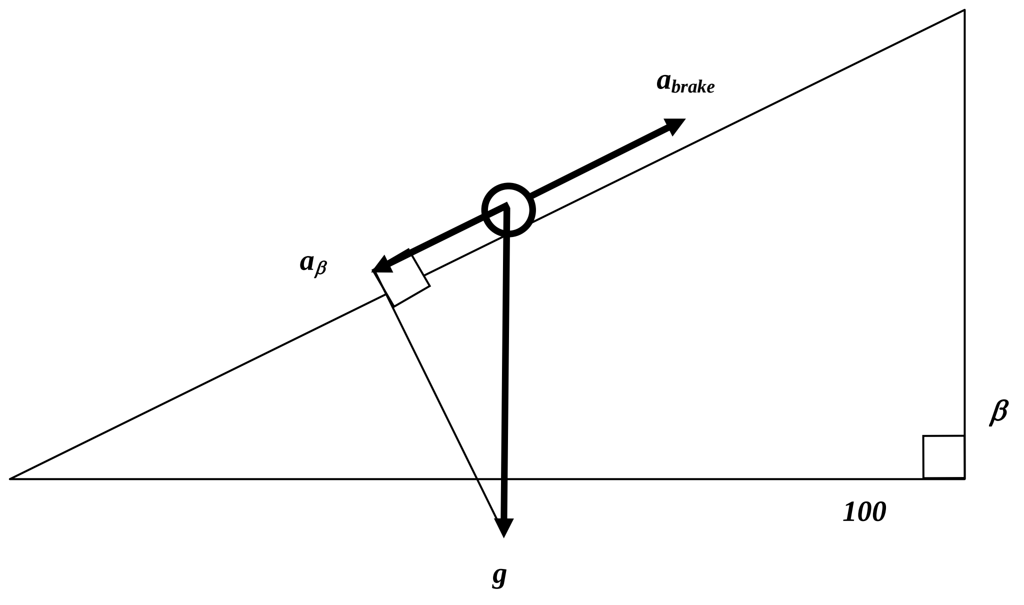
Where $a_{brake-test}$ = acceleration measured along the test grade (m/s^2)

$v =$ the test velocity of the machine immediately prior to the brake control being activated (m/s).

$V =$ the test velocity of the machine immediately prior to the brake control being activated (km/h).

$s =$ the stopping distance along the test grade (m)

3.2 The Maximum Design Grade For Service And Secondary Brakes



Braking accelerations during braking on the maximum permissible design grade of β %

The deceleration on the maximum design grade is

Equation 4 $a_{safe-nett} = a_{brake} - a_{\beta}$

Where $a_{safe-nett}$ =the minimum safe nett deceleration along the maximum design grade (m/s²) and the suggested criteria for brake testing is as follows:

= 0.60 (m/s) service brake (in-service testing)

= 0.75 (m/s) *s*ervice brake design (125% of in-service testing)

= 0.30 (m/s) secondary brake (in-service testing)

= 0.40 (m/s) secondary brake design (125% of in-service testing)

a_{brake} = maximum braking deceleration on level ground (m/s²)

a_{β} = acceleration along the maximum design grade due to gravity (m/s²)

And a_{β} can be calculated from

***Equation* 5a** $a_{\beta} = g \sin \tan^{-1}\left(\frac{\beta}{100}\right)$

Where g = acceleration due to gravity = 9.81 (m/s²)

β = maximum design grade as a % for example, if β = 15, the maximum design grade is 15% or $\frac{15}{100}$. Note: β is never less than 10

This equation can be rewritten as:

Equation 5b $a_{\beta} = g\left(\frac{\beta}{\sqrt{100^2 + \beta^2}}\right)$

Now if $D = \frac{\beta}{\sqrt{100^2 + \beta^2}}$ = design grade function (D), then *Equation 4b* can be rewritten as

Equation 5c $a_{\beta} = g(D)$

Combining *Equations 1 and 4* to eliminate a_{brake} gives

Equation 6a $a_{brake-test} = a_{safe-nett} + a_{\beta} - a_{\alpha}$

Substituting for a_{α} *and* a_{β} *gives*

Equation 6b $a_{brake-test} = a_{safe-nett} + g\left(\frac{\beta}{\sqrt{100^2 + \beta^2}} - \frac{\alpha}{\sqrt{100^2 + \alpha^2}}\right)$

A simplified version for practical use is:

Equation 6c $a_{brake-test} = a_{safe-nett} + g(D - T)$

Hence, if the maximum design grade (*β)*, the test grade (α) and the minimum safe nett deceleration ($a_{safe-nett}$) required along the maximum design grade are all known, then the required deceleration measured along the test grade will be $a_{brake-test}$ as shown in *Equation B*

3.3 *Changes To Vehicle Mass And Brake System Pressures*

Now if the vehicle is to operated in-service at a lesser mass than the GVM, then the available deceleration for stopping is higher.
Similarly if the brake system pressure reduces, then the available brake deceleration is lower. Both of these are proportional to the deceleration via F=ma.

Therefore *Equation 6c* above can be rewritten as,

Equation A $$a_{brake-test} = \left(a_{safe-nett} + g(D-T)\right)\left(\frac{100}{100-P}\right)\left(\frac{m_{GVM}}{m_{actual}}\right)$$

Where $P =$ percentage reduction in braking force

m_{actual} = actual mass of the machine being tested (kg)

m_{GVM} = Gross vehicle mass of the machine (kg)

3.4 *Stopping Distance During Testing Along Any Test Course, Of Any Grade*

Combining *Equations 3b and A* to eliminate $a_{brake-test}$ gives

Equation 7 $$\frac{V^2}{25.92s} = \left(a_{safe-nett} + g(D-T)\right)\left(\frac{100}{100-P}\right)\left(\frac{m_{GVM}}{m_{actual}}\right)$$

Rearranging for "s" gives

Equation B $$s = \left(\frac{V^2}{25.92\left[a_{safe-nett} + g(D-T)\right]}\right)\left(\frac{100-P}{100}\right)\left(\frac{m_{actual}}{m_{GVM}}\right)$$

3.5 *Finding The Maximum Design Grade*

Rearranging *Equation* A and solving for β gives

Equation C $$\beta = 100\tan\sin^{-1}\left[\frac{\left(\left(\frac{100-P}{100}\right)\left(\frac{m_{actual}}{m_{GVM}}\right)\left(a_{brake-test}\right) - a_{safe-nett}\right)}{g} + T\right]$$