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Roller Brake Tester Measurement Uncertainty Calculation

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Abstract –

This article contains a description of the technical, process-related and organizational procedures which accredited calibration laboratories use as a model for defining internal processes and regulations. By implementing these procedures, it is ensured that the devices to be calibrated are all treated equally in the various calibration laboratories and that the continuity and comparability of the work of the calibration laboratories are improved. The calibration certificates issued by the accredited laboratories prove the traceability to national standard as required by Standard HRN EN ISO/IEC 17025:2017 [1].

This procedure defines minimum requirements to be met by work area and equipment required to calibrate a measuring instrument used for measuring braking force on the periphery of wheels of road vehicles (hereinafter: roller brake tester), as well as the calibration procedure and the estimation of the measurement uncertainty. This article describes static method for calibration of roller brake testers.

Some of the measurement uncertainty contributions stated in this document as most relevant contributions that have to be considered during uncertainty calculation, may still be exempted from measurement uncertainty calculation. In those cases calibration laboratory must prove the exemption by reasonable means such as calculations, measuring results, statistics, etc.

Keywords – measurement uncertainty; roller brake tester; calibration.

I. INTRODUCTION

This procedure defines minimum requirements to be met by work area and equipment required to calibrate a measuring instrument used for measuring braking force on the periphery of wheels of road vehicles (hereinafter: roller brake tester or RBT), as well as the calibration procedure and the estimation of the measurement uncertainty for static method.

II. DESCRIPTION OF THE METHOD

This article describes static method for calibration of roller brake testers.

The procedure for roller brake tester calibration complies with the manufacturer's instructions and is described in the standard operating procedures for individual types of rollers.

Work area

Since the roller brake tester is a stationery device, it is usually calibrated at a vehicle inspection station or a repair shop that has adequate space (a hall) to house such a device.

The area where calibration is performed must be properly maintained and protected from adverse effects, such as moisture, dust, heat, vibrations and electromagnetic interference.

The area must be large enough to reduce the risk of damage or other hazardous situations and to ensure that metrologists can perform their tasks uninterrupted.

Environmental conditions must be within the limits defined by the manufacturer of the roller brake tester.

Equipment

Calibration equipment consists of working standard with accessories, testing vehicle and thermo-hygrometer.

The working standard is calibrated in an accredited laboratory or national metrology institute and provided with a calibration certificate stating the expanded uncertainty at the time of calibration. Also the working standard is calibrated at regular intervals according to local metrology legislation and provided with a calibration certificate stating the expanded measurement uncertainty under standard conditions.

Calibration procedure

Preliminary operations

Before calibration, the following actions must be carried out:

1. Identifying the roller brake tester and establishing environmental conditions.
2. Checking the general condition of the roller brake tester.
3. Checking the functionality of the roller brake tester.

If all three actions do not give positive result, calibration cannot be performed.

Device testing

The accuracy of the roller brake tester is tested by comparing the force values which are displayed on the brake tester and force values measured by working standard, according to standard operating procedures depending on the type of the roller brake tester.

Brake roller tester – General information

Table 1 gives main definitions that is used in this article.

Table 1 Definitions

Label	**Description**	**Measuring unit**
F_5	Working standard force	N
Fn	Measured force	N
l	Characteristic of the brake tester model (length of the lever)	mm
$u(l)$	Standard uncertainty of calibration of the distance from the center of the roller to the center of the calibration (tollerance given by manufacturer)	mm
K	Roller brake tester's constant (it depends on roller's construction)	mm
u_c	Combined standard uncertainty in each calibration point	N
k	Coverage factor (k=2, for normal distribution the assigned expanded uncertainty corresponds to a coverage probability of approximately 95 %)	-
$r_{\max}$	Maximum deviation of the measured roller radius from the arithmetic mean	mm
r_{sr}	Arithmetic mean of radius of rollers	mm
α	Pushrod offset angle from the vertical in the direction x (see Figure 3)	°
β	Pushrod offset angle from the vertical in the direction y (see Figure 3)	°
U	Expanded measurement uncertainty	N
u_Δ^2	Variance of pushrod verticality	N^2
$u^2(r)$	Roller radius variance	mm^2
$u^2(F_5)$	Variance of working standard force	N^2
u_x	Pushrod estimated verticality deviation in direction x	N
u_y	Pushrod estimated verticality deviation in direction y	N
u_Δ	Pushrod estimated verticality deviation	N
$u_{\text{repeatability}}^2$	Variance due to the repeatability of the measurement	N^2
P_{analogue}	Resolution (analogue scale)	N
u_{digit}	Digit step of roller brake tester	N
x, y, z	Spatial axis (see Figure 3)	-
$d_1, \dots, d_n$	Measured diameter of rollers	mm
$u_{\text{resolution}}^2$	Variance of roller brake tester due to the resolution	N^2
u_{standard}^2	Variance of working standard	N^2
$u^2(K)$	Variance due to the length lever (distance from the center of motor of roller to the calibration hole center)	mm^2

The principle of braking force measurement

Braking force is defined as the force of the wheels applied in an effort to stop the rollers of the roller brake tester, and is calculated from the reactive force of stator of the electric motor that drives the rollers.

Braking force on the rollers is transferred by chain from the roller sprocket to the drive sprocket (Fig. 1.). The drive sprocket is fixed to the shaft of the driving unit’s rotor. The force transferred by sprocket to the electric motor’s rotor results in a reaction in the electric motor’s stator, trying to rotate the stator in the direction opposite to the direction of rotation of the rotor. Since the entire driving unit is mounted only by the shaft of the electric motor, and the stator rests on solid surface only by means of the lever $l_1$and the measuring component, the lever $l_1$transfers the reaction between the rotor and the stator of the electric motor to the measuring component. The measuring component converts the measured force into an electric signal which is sent to the computer. The computer calculates the received signal into braking force according to the equation (5).

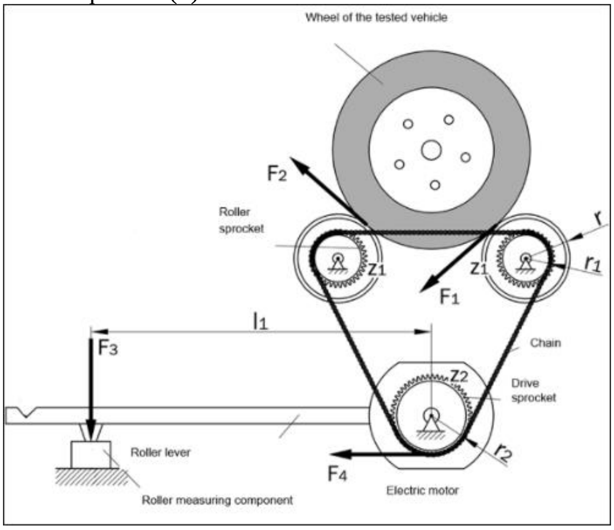

Figure 1 Principle of braking force measurement – mechanical model

The principle of measuring braking force on rollers can be demonstrated on the mechanical model shown in Figure 1. Equation (1) gives total braking force transferred from the wheels of the tested vehicles to rollers

$$F = F_1 + F_2 \qquad (1)$$

From the equilibrium conditions of rollers, the relationship between the braking force and the force transferred by chain /rigid connection/ to the measuring component is given in (2):

$$F \cdot r = F_4 \cdot r_1 \qquad (2)$$

From the equilibrium conditions of the roller lever it follows as in (3):

$$F_4 \cdot r_2 = F_3 \cdot l_1 \qquad (3)$$

From the geometry of the mechanism, the gear ratio is given in (4)

$$\frac{r_2}{r_1} = \frac{z_2}{z_1} \qquad (4)$$

By applying the above expression, the force exerted on the measuring component can be expressed as a function of the braking force as is shown in (5).

$$F_3 = F \cdot \frac{r}{l_1} \cdot \frac{z_2}{z_1} \qquad (5)$$

Testing with working standard

When testing roller brake testers, the working standard’s push lever exerts the force on the roller’s measuring component. The distance from the point of action of the push lever on the roller lever to the rotation axis of the electric motor is designated as l as is shown on Figure 2. The force exerted by the working standard on the roller lever is equal to the force on the measuring component of the working standard (F_5). Depending on the model of the brake tester, the force (F_5) can be tensile or compressive. The point where the roller lever rests on the measuring components of the rollers is at the distance l_1 from the rotation axis of the electric motor.

From the equilibrium conditions of the roller lever, the force exerted on the measuring component F_6 is expressed as the function of force of the working standard’s push rod given in (6)

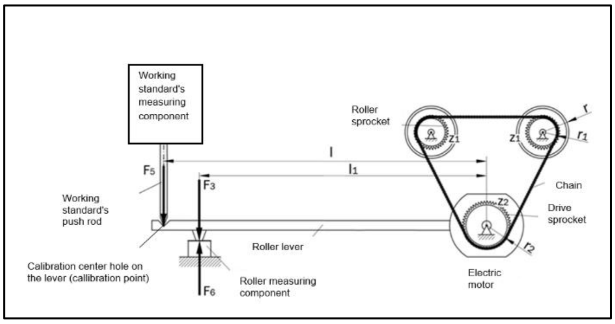

Figure 2 Testing of rollers using the working standard – mechanical model

$$F_6 = F_5 \cdot \frac{l}{l_1} \qquad (6)$$

The expression for calculating the braking force in relation to the force that the working standard exerts on the roller measuring component is derived from the equality of expressions (5) and (6).

When the expression (6) is inserted in the expression (5), where $F_3 = F_6$, the obtained result is given in (7).

$$F = F_5 \cdot \frac{l}{r} \cdot \frac{z_1}{z_2} \qquad (7)$$

It follows that F is given as is in (8)

$$F = \frac{K}{r} \cdot F_5 \qquad (8)$$

Where K is given in (9)

$$K = l \cdot \frac{z_1}{z_2} \qquad (9)$$

where K is the constant of the roller brake tester, depending on its type.

The expression (9) provides the final ratio between the braking force and the force exerted by working standard on the roller lever. Since the constant K is different for every type or construction of roller brake tester it must be calculated for every type or construction of roller brake tester. The number of testing points depends on the measurement range of the roller brake tester, with at least 5 points of measurement.

Evaluation of measurement uncertainty

The following sources of uncertainty may occur when reporting the result of measurement and its uncertainty:

- Measurement uncertainty of the working standard
- Measurement uncertainty due to the brake tester resolution
- Pushrod estimated verticality deviation
- Uncertainty due to the repeatability of the measurement
- Uncertainty due to the distance from the center of motor of the roller to the calibration hole center on roller lever
- Uncertainty of calibration of the distance from the center of motor of the roller to the calibration hole center
- Uncertainty of the measuring forces
- Uncertainty due to the roller diameter
- Uncertainty of measurement of the roller diameter
- Uncertainty due to the length meter
- Uncertainty due to the repeatability of the diameter measurement

Depending on the calibration procedure, the following elements are the most relevant in the evaluation of measurement uncertainty of roller brake tester calibration:

- Measurement uncertainty of the working standard
- Measurement uncertainty due to the brake tester resolution
- Measurement uncertainty due to the inclination of the working standard’s push rod
- Measurement uncertainty due to roller diameter
- Distance from the center of the roller to the calibration hole center on roller lever
- Repeatability of the measurement

Estimation of combined measurement uncertainty

Before calculating the combined measurement uncertainty, it is necessary to put the data from all sources to the same level of confidence, i.e. to the standard uncertainty u.

If the estimate of the measurand y is given by the function dependence of the input estimates x_i [2] as in (10)

$$y = f(x_1,\ x_2, \dots, x_i) \qquad (10)$$

then the standard uncertainty is associated with the estimate y, of the output size given by the expression (11)

$$u(y) = \sqrt{\sum_i (C_i \cdot u(x_i))^2},\ C_i = \frac{\partial y}{\partial x_i} \qquad (11)$$

herein C_i is sensitivity coefficient describing how the output estimate y varies with changes in the values of the input estimates x_i where is presumed that there is no correlation between x_i. The sensitivity coefficient C_i is actually a partial derivation of the function y of the model by the input magnitude x_i.

The expanded uncertainty U is obtained by multiplying the combined standard uncertainty $u_c(y)$ by a coverage factor k (k=2 gives an interval that has a confidence level of approximately 95 %).

The result of a measurement is then expressed as in (12)

$$y \pm U(y) = y \pm k \cdot u(y) \quad (12)$$

In our case measurement model is given in (13)

$$F = \frac{K}{r} \cdot F_5 \qquad (13)$$

where K is given in (14)

$$K = l \cdot \frac{z_1}{z_2} \cdot \qquad (14)$$

Equation (15) gives the standard uncertainty $u_c(F)$ in each calibration point

$$u_\mathrm{c}(F) = \sqrt{(C_\mathrm{K} \cdot u(K))^2 + (C_\mathrm{r} \cdot u(r))^2 + \left(C_{F_5} \cdot u(F_5)\right)^2}$$
$$(15)$$

Sensitivity coefficients are calculated by formulas (16), (17) and (18).

$$C_\mathrm{k} = \frac{\partial F}{\partial K} = \frac{F_5}{r} \qquad (16)$$

$$C_\mathrm{r} = \frac{\partial F}{\partial r} = -\frac{K}{r^2} \cdot F_5 \qquad (17)$$

$$C_{F_5} = \frac{\partial F}{\partial F_5} = \frac{K}{r} \qquad (18)$$

Combined standard uncertainty u_c in each calibration point is shown in (19).

$$u_\mathrm{c} = \sqrt{u_\mathrm{c}^2(F) + u_\mathrm{resolution}^2} \qquad (19)$$

When formulas (16), (17) and (18) for sensitivity coefficients are inserted in (15), formula for combined standard uncertainty is given in (20).

$$u_\mathrm{c} = \sqrt{\begin{gathered}\left(\frac{F_5}{r} \cdot u(K)\right)^2 + \left(-\frac{K}{r^2} \cdot F_5 \cdot u(r)\right)^2 \\ + \left(\frac{K}{r} \cdot \mathrm{u}(F_5)\right)^2 + u_\mathrm{resolution}^2\end{gathered}} \qquad (20)$$

Relevant influence quantities of the calibration item for the uncertainty budget

Uncertainty due to the lever length

Uncertainty due to the lever length is expressed by (21), where K is the constant of the roller brake tester and depends on characteristic of the brake tester model (length of the lever) l as is shown in expression (9). Variance due to the length lever is then calculated by (22)

$$u(K) = \frac{u(l)}{\sqrt{3}} \qquad (21)$$

$$u^2(K) = \frac{u^2(l)}{3}\ \mathrm{mm}^2 \qquad (22)$$

where $u(l)$ is the standard uncertainty of calibration of the distance from the center of the roller to the center of the calibration, that is estimated as a rectangular distribution. This tolerance is given by the manufacturer or it can be reasonably estimated by metrologists involved in calibration.

Standard measurement uncertainty due to roller radius

Maximum deviation of all roller radiuses from the arithmetic mean is given by formula (23)

$$r_\mathrm{max} = \max\left(|r_\mathrm{sr} - r_1|, |r_\mathrm{sr} - r_2|, |r_\mathrm{sr} - r_3|, |r_\mathrm{sr} - r_4|, \dots\right) (23)$$

where $r_1, r_2, r_3 \dots$ are measured radiuses where at least the largest and the smallest diameter of the rollers is measured and where $r_i = \frac{d_i}{2}$. of rollers and r_{sr} is arithmetic mean of radius of rollers as is shown in (24)

$$r_\mathrm{sr} = \frac{\sum_{i=1}^{4} r_i}{4}\ mm \quad (24)$$

Roller radius variance $u^2(r)$ is then calculated by (25)

$$u^2(r) = \frac{1}{3} \cdot (r_\mathrm{max})^2\ \mathrm{mm}^2 \quad (25)$$

Standard measurement uncertainty due to working standard force

Standard measurement uncertainty due to working standard forces $u(F_5)$ consists of several contributions given in (26).

$$u^2(F_5) = u_\mathrm{repeatability}^2 + u_\Delta^2 + u_\mathrm{standard}^2 \qquad (26)$$

Standard measurement uncertainty of working standard

Working standard uncertainty is a source of uncertainty in measurement that should be included in the uncertainty budget.

Measurement uncertainty of the standard is determined based on the data from the certificate of calibration of the working standard. At least, it can be taken from the calibration certificate at the calibration point at which measurement uncertainty and its belonging deviation give the biggest sum.

Absolute measurement uncertainty $U^{`}_\mathrm{standard}$ is taken from certificate of calibration and is calculated as (27):

$$U^{`}_\mathrm{standard} = \frac{2 \cdot |K_0|}{\sqrt{3}} + U \qquad (27)$$

where U is measurement uncertainty of working standard and K_0 is deviation with expected value.

Then there is:

$$u^{`}_\mathrm{max} = \frac{U^{`}_\mathrm{standard}}{2} \qquad (28)$$

If measurement uncertainty of a working standard is given in [kg], maximum measurement uncertainty taken from the certificate of calibration is given by (29)

$$u^{`}_\mathrm{standard} = u^{`}_\mathrm{max} \cdot g \qquad (29)$$

Measurement uncertainty of working standard must be multiplied by a roller brake tester's constant K, and multiplied by roller brake tester radius r.

The estimated standard uncertainty of working standard is then as shown in (30):

$$u_{\text{standard}} = \frac{K}{r} \cdot u\grave{}_{\text{standard}} \quad (30)$$

Pushrod estimated verticality deviation

Pushrod estimated verticality deviation u_Δ^2 is given by (31)

$$u_\Delta^2 = \frac{1}{3} \cdot u(\Delta)^2 \quad (31)$$

where $u(\Delta)$ is working standard uncertainty of pushrod verticality and is given by (32)

$$u(\Delta) = u = \sqrt{u_x^2 + u_y^2} \quad (32)$$

where u_x is pushrod estimated verticality deviation in direction x and u_y is pushrod estimated verticality deviation in direction y as given by (33) and (34). Also, u_x and u_y are independent values.

$$u_x = F_n - \cos\alpha_{\max} \cdot F_n \quad (33)$$
$$u_y = F_n - \cos\beta_{\max} \cdot \mathrm{F_n} \quad (34)$$

α : pushrod offset angle from the vertical in the x direction
β : pushrod offset angle from the vertical in the y direction
F_n : measured force

α or β can be reasonably estimated by metrologist performing calibration.

Uncertainty due to the repeatability of the measurements

Repeatability is estimated using the standard deviation S_R as is shown in (35)

$$u_{\text{repeatability}}^2 = S_{\mathrm{R}}^2 = \frac{s^2}{n_{\mathrm{F}}} \quad (35)$$

where n_{F} is the number of measurements of each force and s^2 is the experimental standard deviation of the mean and is calculated by (36)

$$s = \sqrt{\frac{1}{n_F - 1} \sum_{i=1}^{n_F} (I_i - \bar{I})^2} \quad (36)$$

where I is calculated by (37)

$$\bar{I} = \sum_{i=1}^{n_F} \frac{I_i}{n_F} \quad (37)$$

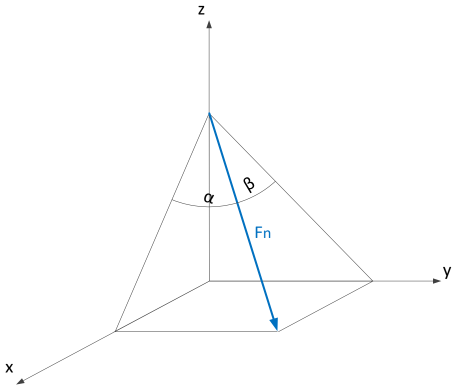

Figure 3 The vector description of force F_n which acts on momentum lever of rollers

The typical uncertainty associated with that term is given by (38)

$$u_{\text{repeatability}} = S_R = \sqrt{\frac{s^2}{n_{\mathrm{F}}}} = \frac{\sqrt{\frac{\sum_{i=1}^{n_F}(I_i - \bar{I})^2}{n_F - 1}}}{\sqrt{n_{\mathrm{F}}}} \quad (38)$$

Measurements of force can be made n_{F} times.

Standard measurement uncertainty of roller brake tester due to resolution

Variance of roller brake tester with analogue scale is calculated by (39):

$$u_{\text{resolution}}^2 = \frac{1}{3} \cdot (u_{\text{res}})^2 \quad (39)$$

where measurement uncertainty of roller brake tester due to resolution u_{res} is usually estimated at 1/5 division of the analogue scale, so then is (40)

$$u_{\text{res}} = \frac{1}{5} \cdot P_{\text{analogue}} \quad (40)$$

where P_{analogue} is resolution of roller's for analogue scale.

Laboratory may decide whether the measurement uncertainty of the roller brake tester due to resolution can be estimated at 1/2 or 1/5 division of the scale, depending on, for example, ratio of thickness of pointers and division scale space, thickness of lines that separate division scale spaces, precision of graphical representation or number resolution.

For devices with digital indication the resolution corresponds to the digit step, so the contribution of the resolution to the uncertainty is estimated as a rectangular distribution and is calculated as (41)

$${u_{\text{resolution}}}^2 = \frac{u_{\text{digit}}^2}{12} \quad (41)$$

III. RESULTS AND DISCUSSIONS

To make proposed budget of measurement uncertainties more clear, an example of the calculation is given at nominal force of 5000 N for the right side of roller brake tester.

In this example resolution of RBT is 3 N, lever length of RBT l is 282 mm, tolerance of lever length $u(l) = 1\,mm$ and the gear ratio is $z_1 = z_2$.

Sources of measurement uncertainty

Standard measurement uncertainty of roller brake tester due to resolution

$$u_{\text{resolution}} = \frac{u_{\text{digit}}}{2 \cdot \sqrt{3}} = \frac{3}{2\sqrt{3}}$$
$${u_{\text{resolution}}}^2 = 0{,}75\,N^2$$

Uncertainty due to the lever length

$$u^2(K) = \frac{u^2(l)}{3} = \frac{1}{3} = 0{,}33\,mm^2$$

Standard measurement uncertainty due to roller radius

$$r_{\text{sr}} = 141{,}5\,mm$$
$$r_{\max} = 0{,}5375\ \text{mm}$$
$$u^2(r) = \frac{1}{3} \cdot (r_{\max})^2 = 0{,}24438\,mm^2$$

Standard measurement uncertainty due to working standard force

$$u^2(F_5) = u^2_{\text{repeatability}} + u^2_{\Delta} + u^2_{\text{standard}}$$

Standard measurement uncertainty of working standard

$$\grave{U}_{\text{standard}} = \frac{2 \cdot |K_0|}{\sqrt{3}} + U = \frac{2 \cdot 0{,}291}{\sqrt{3}} + 0{,}07 = 0{,}406\ kg$$

$$\grave{u}_{max} = \frac{\grave{U}_{\text{standard}}}{2} = 0{,}203\ kg$$

$$\grave{u}_{\text{standard}} = \grave{u}_{\text{max}} \cdot g = 1{,}991\ N$$

$$u_{\text{standard}} = \frac{K}{r} \cdot \grave{u}_{\text{standard}} = \frac{282}{141{,}23} 1{,}991 = 3{,}967\ N$$

$${u_{\text{standard}}}^2 = 15{,}739\ N^2$$

Pushrod estimated verticality deviation

$$u_x = F_n - \cos\alpha_{\text{max}} \cdot F_n = 4975{,}8 - 4975{,}8 \cdot \cos 3° = 6{,}81916\ N$$

$$u_{\text{y}} = u_{\text{x}} = 6{,}81916\ N$$

$$u(\Delta) = \sqrt{u_{\text{x}}^2 + u_{\text{y}}^2} = 9{,}636\ N$$

$$u_{\Delta}^2 = \frac{1}{3} \cdot u(\Delta)^2 = 31{,}00063\ N^2$$

Uncertainty due to the repeatability of the measurements

$$F_{\text{n}} = \bar{I} = \frac{4974 + 4977 + 4974 + 4977 + 4977}{5} = 4975{,}8\ N$$

$$s = 2{,}7\ N$$

$$u_{\text{repeatability}} = S_{\text{R}} = \sqrt{\frac{s^2}{n_{\text{F}}}} = \frac{2{,}7}{\sqrt{5}} = 1{,}21\ N$$

$${u_{\text{repeatability}}}^2 = 1{,}46\ N^2$$

Standard measurement uncertainty due to working standard force is then:

$$u^2(F_5) = u^2_{\text{repeatability}} + u^2_{\Delta} + u^2_{\text{standard}}$$

$$u^2(F_5) = 1{,}46 + 31{,}00063 + 15{,}739 = 48{,}20945\ N^2$$

In this example, from Table 2 it is obvious that resolution has negligible contribution in measurement uncertainty, while the roller diameter measurement has significant contribution in measurement uncertainty. Also, repeatability of measured force has negligible contribution, so it can be excluded from calculation of measurement uncertainty.

Significance of components

Table 2 Table of components of measurement uncertainty

Description	Variance	Sensitivity coefficient	Uncertainty contribution	
			(abs.)	(%)
Lever length	0,33 mm^2	1248,39 N^2/mm^2	416,13 N^2	22,87
Roller radius	0,24 mm^2	4957,46 N^2/mm^2	1211,51 N^2	66,57
Working standard force	48,21 N^2	3,97 mm^2/ mm^2	191,44 N^2	10,52
Resolution	0,75 N^2	1 N^2	0,75 N^2	0,04
u_c^2=1819,83 N^2				
Measurement uncertainty u_c=42,66 N				
Expanded measurement uncertainty U=86 N				

Measurement uncertainty

$$u_c = \sqrt{\left(\frac{F_5}{r} \cdot u(K)\right)^2 + \left(-\frac{K}{r^2} \cdot F_5 \cdot u(r)\right)^2 + \left(\frac{K}{r} \cdot \mathrm{u}(F_5)\right)^2}$$

$$u_{\text{c}} = 42{,}7\ N$$

Expanded measurement uncertainty

$$U = k \cdot u = 2 \cdot 42{,}7\ N = 86\ N$$

IV. CONCLUSIONS AND OUTLOOK

Calibration of roller brake testers and resulting measurement uncertainty depend on many influential factors that are briefly described due to limitations of this article. Depending on roller brake tester construction and calibration method, those influences must be used in the measurement uncertainty calibration, and some of them could be neglected if not contributing enough to the measurement uncertainty. Since roller brake testing is rough and swift method to estimate correct functioning of brakes on vehicles, there is no need for laboratory precision, so use of uniform probability distribution is used in variance formulas to facilitate simplicity and avoid unnecessary additional calculations and proving. Main sources of measurement uncertainty are outlined in this article with corresponding example of their use in the calculation hoping that this could be a proposal of standard static method procedure for use throughout laboratories that deal with this kind of calibration of roller brake testers.

V. ACKNOWLEDGMENTS

We would like to express our gratitude to Mrs. Iva Magdalenić, B.S.M.E, whose suggestions and big contribution made this article possible.

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