A proposal for dynamic calibration of brake tester

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Abstract. In Brazil there are about 400 security inspection lines carrier operating in Inspection Bodies accredited by Cgcre Inmetro [1]. The equipment in this proposal is a Brake Tester that measure vehicle braking forces and it is a component of an inspection line. This paper proposes a dynamic Brake Tester calibration using a reference torque transducer. This article can also be the basis for future discussions of the revised standard manufacturing of vehicle inspection line according to ABNT NBR 14040 [2].

1. Introduction
The Brazilian standard that specifies the manufacture of vehicle inspection lines (Figure 1) ABNT NBR 14040 [2] does not include metrological criteria to be met and also does not mention how the equipment must be calibrated.

1;2 Side-slip test
3 Shock absorber inspection
4 Brake tester
5 Lift unit
6 Gas analyser
7 Opacimeter
8 Light alignment

Figure1- Example vehicle inspection line

The traditional method of Brake Testers calibration used by manufacturers is static. Consists of applying a calibrated weight placed on the end of the arm installed on the electric motor traction shaft Brake Tester these methodology is not efficient for calibration because it does not consider the actual dynamic vehicle in operation and the variables corresponding to the roller mechanism of the Brake Tester, as well as friction characteristics of the tires and brake friction elements, etc.

2. Purpose
This work aims to present a dynamic methodology calibration of a Brake Tester, figure 2. In this methodology the Brake Tester is calibrated by comparing its indicated strength with a reference standard torque transducer and the use of a special vehicle to meet the conditions of the test.
The methodology can serve as a basis for establishing metrological tolerances for Brake Testers, considering the linear and angular coefficients of the calibration curves of these instruments and the measurement uncertainty.

3. Methodology proposal

3.1. Performance of the test

The performance of the test as proposed it consists the installation of a calibrated torque transducer and an encoder on the vehicle wheel axle for measurements of force and its tangential speed. Another Brake Tester encoder is placed on the traction roll to measure its tangential velocity, as shown in Figure 3. This set will be called brake reference.

In brake reference the wheel and encoders measure the different roller speeds, however before the start of braking there is no slippage between the roller and the wheel. Thus, the respective circumferential speeds are equal. Thus, this equation can be written by equation 1.
Where:

\[
\begin{align*}
\omega_{\text{roll}} &= \text{The roll angular velocity (rpm)}; \\
\omega_{\text{wheel}} &= \text{Wheel angular velocity (rpm)}; \\
\phi_{\text{roll}} &= \text{Roller diameter (mm)}; \\
\phi_{\text{wheel}} &= \text{Wheel Diameter (mm)}; \\
\end{align*}
\]

Of equation above are known: the roll speed, roll diameter and wheel speed. Thus, the effective diameter of the wheel is defined by the equation

\[\phi_{\text{wheel}} = \frac{\omega_{\text{roll}} \cdot \phi_{\text{roll}}}{\omega_{\text{wheel}}} \quad (2)\]

The wheel diameter should be calculated according to the equation 2, because there is a deformation of the tire due to its support on the roll. Known effective diameter of the wheel and therefore its radius, the reference torque is converted into power which reference is compared with the strength indication Brake Tester.

The purpose of Brake Tester as control and monitoring tool is to record the maximum braking force that is obtained when the wheel speed reaches 20% to 30% of the roller speed [2]. At full strength, the measurement process is quite turbulent and this instability prevents one Brake Tester repeatability study this measuring point. In order to avoid instability, measurements are carried out in stages. A threshold means to maintain a constant nominal power brake by a predetermined period of time (Figure 4) called baseline, which can perform the registration of the force measured by Brake Tester compared with the reference value measured by the torque transducer.

At the beginning of the measurements indicates Brake Tester forces before the brake application by the driver, which forces are called parasites. These forces correspond to the resistance to movement system (rollers, wheels, transmission system, etc.) that is registered by the load cell Brake tester and are not detected by Brake reference. The parasitic forces should be discounted in the mathematical model that defines the amount recorded by Brake Tester when compared to the value as equation 3.
For the test to be carried out under reproducibility conditions of the test operators (vehicle driver and technician responsible for measurements) were previously trained. Also a special vehicle to meet the conditions of the test with brake system working properly. The vehicle tire pressure were set at 45 psi (310 kPa) before each test. During the test run, the vehicle was moved from one installation to another towed. The measurement was set out of the rear axle, which is rigid with measurements results in lower dispersion values. The reference standard installed on the axis of the vehicle was assembled and disassembled each experiment by trained technician to avoid potential problems on shipping. The braking of the vehicle during each test was performed by the operator of the evaluated inspection line.

3.2 Establishment of the calibration curve model
Whereas the vehicle used produces a maximum braking force on the order of 1800 N, was chosen four set points force (measuring levels) in 400N; 800N; 1100N and 1400N. The test was performed in descending order of strength. For each nominal point of measurement were considered five medium arising from an acquisition of 20 Hz rate (20 samples per second) continuous measurement that equals approximately 200 values.

In possession of all the results of averages for each of the nominal values and their reference values, Brake Tester calibration curve can be defined by the model of equation 3:

\[ F_{ref} = a + b \cdot (F_i - F_p) \]  

Where:

- \( a \) = linear coefficient (C);
- \( b \) = slope;
- \( F_i \) = Brake Tester force indicated by (N);
- \( F_p \) = Force parasite (N).

The systematic error of Brake Tester was evaluated by linear coefficient of its calibration curve according to the new methodology proposed by this work. The slope measures the specific property of each Brake Tester, comprising the drive mechanism of the rollers, placement of meters and sensors as geometry of each project, etc.

3.3 Validation of the calibration curve model
The validation of the Brake Tester calibration curve model was carried out by residual analysis and variances [3].

3.4 Measurement uncertainty
Estimation of the calibration of a Brake Tester measurement uncertainty followed the ISO GUM recommendations in 2008 [4].
3.4.1 Measuring
The measured calibration of an Brake Tester was defined by the force value that evaluated the timely systematic error of the instrument, according to equation 4.

\[
\bar{e}_i = \bar{F}_i - \bar{F}_p - \bar{F}_{ref} = \bar{F}_i - \bar{F}_p - \left( \frac{\Delta V - a_i}{b_i} \right) \cdot \frac{2}{\phi_{wheel}}
\]  

(4)

Where:
- \( \bar{F}_i \) = Medium strength indicated by Brake Tester (N);
- \( \bar{F}_p \) = Force average parasite (N);
- \( \bar{F}_{ref} \) = Reference average force (N);
- \( a_i \) = Linear coefficient of the calibration curve of the torque transducer (V);
- \( b_i \) = Slope of the torque transducer calibration curve (V / Nm);
- \( \Delta V \) = Medium voltage indicated by the transducer (V) calibration;
- \( \phi_{wheel} \) = Mean wheel diameter (m) according to equation 2;

3.4.2 Cause-Effect Diagram
According to equation 4, the uncertainty sources are shown in the diagram cause effect of Figure 5:

![Figure 5 Diagram Cause Effect of estimated Brake Tester error uncertainty](image-url)
3.4.3. Uncertainties of the input quantities

3.4.3.1 Wheel diameter

The uncertainties related to roll angular velocity ($\omega_{\text{roll}}$) of the wheel ($\omega_{\text{wheel}}$) and roll diameter are estimated using the equations 5, 6 and 7, respectively.

$$u_{\sigma_{\text{roll}}} = \left( \frac{5}{n_{\omega_{\text{roll}}}} \left( \frac{s_{\omega_{\text{roll}}}}{n_{\omega_{\text{roll}}}} \right)^2 + \frac{a_{\text{resolution } \sigma_{\text{roll}}}}{3} \right)^{1/2}$$  \hspace{1cm} (5)

$$u_{\sigma_{\text{roda}}} = \left( \frac{5}{n_{\omega_{\text{wheel}}}} \left( \frac{s_{\omega_{\text{wheel}}}}{n_{\omega_{\text{wheel}}}} \right)^2 + \frac{a_{\text{resolution } \sigma_{\text{wheel}}}}{3} \right)^{1/2}$$ \hspace{1cm} (6)

$$u_{\phi_{\text{roll}}} = \frac{a_{\text{resolution } D_{\text{roll}}}}{\sqrt{3}}$$  \hspace{1cm} (7)

Where:

$s_{\omega_{\text{roll}}}$ = Standard deviation of the angular roll speed values;

$n_{\omega_{\text{roll}}}$ = Number of repetitions of the values of the angular speed of the roll;

$a_{\text{resolution } \omega_{\text{roll}}}$ = Scanning resolution of the angular speed of the roll;

$s_{\omega_{\text{wheel}}}$ = Standard deviation of the angular wheel speed values;

$n_{\omega_{\text{wheel}}}$ = Number of repetitions of the angular wheel speed values;

$a_{\text{resolution } \omega_{\text{wheel}}}$ = Scanning resolution of the angular speed of the wheel;

$a_{\text{resolution } \phi_{\text{roll}}}$ = Reading resolution of the roll diameter.

From equation 2 to the uncertainty of the wheel diameter is then defined by Equation 8.

$$u_{D_{\text{wheel}}} = \left( \frac{\partial \omega_{\text{wheel}}}{\partial \omega_{\text{roll}}} \cdot u_{\omega_{\text{roll}}} \right)^2 + \left( \frac{\partial \omega_{\text{wheel}}}{\partial \phi_{\text{roll}}} \cdot u_{\phi_{\text{roll}}} \right)^2 + \left( \frac{\partial \omega_{\text{wheel}}}{\partial \omega_{\text{wheel}}} \cdot u_{\omega_{\text{wheel}}} \right)^2 \right)^{1/2}$$ \hspace{1cm} (8)
3.4.3.2 Strength Indicated by Brake Tester $F_i$

3.4.3.3 Uncertainty on the settlement

The uncertainty regarding the resolution of force indicated by Brake Tester is estimated by equation 9.

$$u_{Fi} = \left( \frac{\sigma_{\text{resolution } F_i}}{3} \right)^{1/2}$$

(9)

Where:

$\sigma_{\text{resolution } F_i} =$ Scanning resolution of the indicated strength.

3.4.3.4 Force Parasite $F_p$.

3.4.3.4.1 Uncertainty on the settlement

The uncertainty related to the parasite replicates force is estimated by equation 11.

$$u_{Fp} = \left( \frac{s_{\text{repetition } Fp}}{n} \right)^{1/2}$$

(10)

Where:

$s_{\text{repetition } Fp} =$ Standard deviation of the values of parasite force;

$n =$ Number of repetitions of the values of parasite force for each nominal value

3.4.3.5 Torque transducer $\tau_{\text{ref}}$

3.4.3.5.1 Uncertainty regarding the calibration certificate of the torque transducer

The uncertainty regarding the calibration certificate of the torque transducer is defined by the equation (11)

$$u_{\text{certificate } \tau} = \frac{U}{100 \cdot k} \cdot \tau_{\text{ref}}$$

(11)

Where:

$U =$ Transducer Certificate uncertainty (%);

$k =$ Certificate coverage factor;
3.4.3.6 Uncertainty regarding the measurement of voltages

Uncertainty regarding the power indicated by the torque meter is estimated by equation 12.

\[
u_{\Delta V} = \left( \frac{5}{\sum_{i=1}^{n} \left( \frac{s_{\Delta V_i}}{n_{\Delta V_i}} \right)^2} + \frac{a_{\text{resolution} \Delta V}}{3} + u_{\text{Interpola} \Delta V}^2 \right)^{1/2}
\]

Where:

\[ s_{\Delta V_i} = \] Standard deviation of the voltage values indicated by the transducer for each set;

\[ n_{\Delta V_i} = \] Number of repetitions of the voltage values indicated for each set;

\[ a_{\text{resolution} \Delta V} = \] Voltage reading resolution

According to [2] the uncertainty related to transducer calibration curve is estimated by equation 13.

\[
u_{\Delta \text{Interpola} \Delta V} = S_e \cdot \left( \frac{1}{m} + \frac{1}{n_t} + \frac{\left( \tau_o - \bar{\tau}_i \right)^2}{m \left( \tau_o - \bar{\tau}_i \right)^2} \right)^{1/2}
\]

Where:

\[ S_e = \] Transducer curve of dispersion (V);

\[ m = \] Number of repetitions of the measurement voltage measurements;

\[ n_t = \] Number of points transducer certificate;

\[ \tau_o = \] Average torque values of the calibrated point;

\[ \tau_i = \] Torque values indicated in the calibration certificate;

\[ \bar{\tau}_i = \] Average voltage values specified in the certificate.

3.4.3.7 Uncertainty relating to the repetitions of machine errors

The uncertainty concerning the dispersion of Brake tester errors is estimated by equation 14.

\[
u_{e_i} = \frac{s}{\sqrt{n}}
\]

Where:

\[ s = \] Standard deviation of Brake Tester errors;

\[ n = \] Number of repetitions
3.4.4 Sensitivity Coefficients
From equation 4, the measuring sensitivity coefficients are calculated by the equations 15, 16, 17, 18 and 19.

\[ c_i(F_i) = \left( \frac{\partial \tilde{e}_i}{\partial F_i} \right) = 1 = c_1 \]  

(15)

\[ c_i(\text{Certificate } \tau) = \left( \frac{\partial \tilde{e}_i}{\partial \text{Certificate } \tau} \right) = -\frac{2}{\phi_{\text{wheel}}} = c_2 \]  

(16)

\[ c_i(\Delta V) = \left( \frac{\partial \tilde{e}_i}{\partial \Delta V} \right) = -\frac{2}{b_1 \cdot \phi_{\text{wheel}}} = c_3 \]  

(17)

\[ c_i(\phi_{\text{wheel}}) = \left( \frac{\partial \tilde{e}_i}{\partial \phi_{\text{wheel}}} \right) = \frac{2(\Delta V - a_1)}{b_1 \cdot \phi_{\text{wheel}}^2} = c_4 \]  

(18)

\[ c_i(e) = \left( \frac{\partial \tilde{e}_i}{\partial e} \right) = 1 = c_5 \]  

(19)

3.4.5 Uncertainty combined calibration of Brake Tester
The combined uncertainty of the systematic Brake Tester error is defined by the equation 20.

\[ u_c(\tilde{e}_i) = \left\{ \left( c_1 \cdot u_{F_i} \right)^2 + \left( c_2 \cdot u_{\text{Certificate } \tau} \right)^2 + \left( c_3 \cdot u_{\Delta V} \right)^2 + \left( c_4 \cdot u_{\phi_{\text{wheel}}} \right)^2 + \left( c_5 \cdot u_{e} \right)^2 \right\}^{1/2} \]  

(20)

3.4.6 Number of effective degrees of freedom
The number of effective degrees of freedom is defined by equation 21.

\[ v_{\text{eff}} = \frac{\left[ u_c(\tilde{e}_i) \right]^4}{\sum_{j=1}^{5} \frac{c_j \cdot u_{\Delta V_i}}{V_{\Delta V_i}}^4 + \frac{c_4 \cdot u_{\phi_{\text{wheel}}}}{V_{\phi_{\text{wheel}}}}^4 + \frac{c_5 \cdot u_{e}}{V_{e}}^4} \]  

(21)

Where:

- \( u_{\Delta V_i} \) = Uncertainties relating to each set of repetitions indicated voltage;
- \( V_{\Delta V_i} \) = Number of degrees of freedom for each set of replicates and the voltage curve;
- \( V_{\phi_{\text{wheel}}} \) = Number of degrees of freedom of the wheel on the combined uncertainty.
3.4.7 Coverage Factor
The coverage factor (k) is defined as the number of effective degrees of freedom computed by the equation 19 and a probability of 95% coverage.

4. Results
The methodology described for the estimation of uncertainty of measurement was applied to calibrate a Brake Tester only a nominal point of 1400 N according to Equation 4 in Table 1 shows the values of the quantities input defining the measurement uncertainty of Brake Tester strength to the point 1400 N.

Table 1. Input quantities defining the calculation of the force measured by a Brake Tester

| Sources          | Value | Unit |
|------------------|-------|------|
| u Fi resolution  | 0.577 | N    |
| u error          | 10.58 | N    |
| uFp              | 0.000 | N    |
| $u_\tau$ certificate | 0.000 | Nm   |
| u $\Delta V$    | 0.001 | V    |
| u $\Phi$ wheel  | 0.002 | m    |

Uncertainty components for each input variable and the combined strength uncertainty measured by Brake Tester are presented in Table 2.

Table 2. Uncertainty components and combined uncertainty.

| Components       | N   | %   |
|------------------|-----|-----|
| $uF(F_i)$        | 0.6 | 0.2 |
| $uF(F_p)$        | 0.0 | 0.0 |
| $uF(\text{error})$ | 10.6 | 71.0 |
| $uF(\text{cerificado})$ | 0.0 | 0.0 |
| $uF(\Delta V)$  | 5.3 | 17.7|
| $uF(\text{roda})$ | 4.2 | 11.1|
| uc               | 12.6|     |
Figure 6 - Force uncertainties balance measured by Brake Tester

Table 3 shows the components of uncertainty in the measured voltage with their respective contributions.

| Source          | Uncertainty(V) | Contribution (%) |
|-----------------|----------------|------------------|
| \( u \Delta V1 \) | \( 3.2 \times 10^{-4} \) | 8.2              |
| \( u \Delta V2 \) | \( 3.1 \times 10^{-4} \) | 7.4              |
| \( u \Delta V3 \) | \( 2.7 \times 10^{-4} \) | 5.7              |
| \( u \Delta V4 \) | \( 2.9 \times 10^{-4} \) | 6.9              |
| \( u \Delta V5 \) | \( 2.6 \times 10^{-4} \) | 5.3              |
| \( u_a \) resolution \( \Delta V \) | \( 5.8 \times 10^{-5} \) | 0.3              |
| \( u \Delta Interpolation \) | \( 9.1 \times 10^{-4} \) | 66.5             |
| \( u \Delta V \) | \( 1.1 \times 10^{-3} \) |                  |

Applying the values in equation 4 of force indicated by Brake Tester parasite strength of the electric voltage measured at the torque transducer and wheel diameter to the nominal point of 1400 N obtains the measurement result measured by the force Brake Tester

\[ 1085 \, N \pm 14N \, (p=95\%; \, k=2.03) \]
In uncertainty (uc F) should be added to the Brake Tester the contribution regarding its calibration curve when it is used as a reference for calibrating the other line inspection. The uncertainty concerning the reference Brake Tester calibration curve is calculated by the expression 22.

\[
u_{\text{curve}Fi} = S_{eF} \left( \frac{1}{m_F} + \frac{1}{n_{IF}} + \frac{(F_o - \overline{F})^2}{\sum (F_i - \overline{F})^2} \right)^{1/2}
\] (22)

Where:

- \(S_{eF}\) = Dispersal Brake Tester curve reference (N);
- \(m_F\) = Number of repetitions of the force measurements indicated by reference Brake Tester;
- \(n_{IF}\) = Number of points of reference Brake Tester certificate;
- \(F_o\) = Average strength values indicated by the reference in the calibrated point;
- \(F_i\) = Strength values given in the calibration certificate in reference Brake Tester;
- \(\overline{F}\) = Average strength values given in reference Brake Tester certificate

5. Conclusions

The values presented show that the nominal point of 1400 N, the predominant element of uncertainty is that regarding the dispersion of machine defects, with a contribution of 71% of the combined force uncertainty.

According to Table 3, the uncertainty of interpolation which comes from the meter calibration certificate torque is the uncertainty that prevails in the electric voltage and whose contribution is approximately 66.3%.

The expanded the aforementioned measurement result uncertainty is approximately 2.7% of the force measured by Brake Tester.

From the obtained measurement result can be observed that the strength of 1400 N indicated by Brake Tester has an error of approximately 22%, which leads to the conclusion that in the current state of the art improvements must be made in equipment for the attenuation of this error, taking into account the uncertainty obtained.

The proposed methodology can be:

- Basis for the realization of inter comparisons in order to continuously be upholding metrological reliability of Brake Testers in the country;
- Used as a tool for the technical management of Brake Testers calibrations as well as aid in the technical guidance for revision of ISO 14040 standard.

Improving the work can be obtained from the acquisition and sync Brake Tester statement data continuously, with the possibility of lowering the instrument error.
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7. References

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